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THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute of Petroleum was held at 61 New Cavendish Street, London, W.1, on 4 May 1960, the Chair being taken by C. M. Vignoles, C.B.E., President of the Institute.

The General Secretary read the minutes of the previous meeting, which were confirmed and signed as a correct record.

The President introduced Mr Chantler, who then presented the following paper in summary.

EUROPE'S ENERGETIC FORECASTING *

By PHILIP CHANTLER †

WHY ENERGETIC FORECASTING?

IN recent years there has been what Messrs Sellar and Yeatman would doubtless call a wave ‡ of energy forecasting—a spate of speculation about future demand and supply of fuel and power. This present wave has not been confined to Western Europe, but it has been so prolonged and so intense here that one may perhaps reasonably telescope two adjectives and speak about "Europe's Energetic Forecasting." The author would offer as a further defence of this title the interpreters' habit of rendering "énergétique" into "energetic"—so that, for instance, "the energetic policy of the United Kingdom" does not necessarily mean what one might think.

There must have been some reason for all this energetic forecasting. In some measure it reflects the larger role which the State has played in economic affairs since the war: most governments have taken a far greater hand in attempting to direct, or at any rate influence, the scale and pattern of economic development than they ever did before 1939, partly because of the general acceptance of Lord Keynes' thesis that the State can, and should, maintain full employment. This implies that governments can, and should, at least forecast the future, even if they cannot control it. So why should they not forecast demand and supply of energy? And why, then, should not collective organizations of governments, like the Organization for European Economic Co-operation, also engage in such forecasting, on behalf of their member countries?

But there is a more specific reason for long-run energy forecasting. A major part of economic planning concerns capital investment. The characteristic of fixed capital investment is that it often takes years to accomplish and can only be worthwhile if it is likely to have a relatively long economic life. To take sound decisions in planning investment, therefore, requires long-term forecasts of demand and supply prospects. One of the main fields of fixed capital investment is in energy supply. Therefore, if governments are to take a hand in planning investment for the supply of energy, they must also engage in forecasting the outlook for energy demand and the prospects of the various alternative energy supplies.

Much of the current energy forecasting, however, seems to be more general and to stretch further ahead than is needed for investment planning. Why? Is is plain intellectual curiosity? Or is it intellectual curiosity whetted by apprehension about the outlook for the human race, or at any rate for Western man?

Again and again, philosophers have been driven to the gloomiest conclusions by the absolute tyranny of simple arithmetic and the remorseless logic of compound interest. For instance, Sir Alexander Grey has pointed out that John Stuart Mill "was flung into an agony of gloom, reflecting that as there is but a limited number of musical tones and semi-tones, and also a limited number of ways in which these may be combined, the world would one day—and that before long—have whistled its last tune" ("The Development of Economic Doctrine" pp. 284–5). Mill died in 1873: there has been quite a lot of music written since then, not all of it using the same theme, and still the supply of new melody does not seem to be wholly extinguished.

Or again, in quite another field, the same sort of frightening arithmetic was recently deployed by an American professor of pharmacology who prognosticated that motorized man is discharging so much carbon dioxide into the atmosphere that it is forming a blanket surrounding the earth which will inevitably capture more heat from the sun, causing a gradual melting of the polar ice caps, so that the oceans will slowly rise and (presumably) ultimately drown all of us in the Thames Valley. To avoid this calamity he prescribes the planting of ten trees for every car and 100 for every lorry, to absorb carbon dioxide and breathe out oxygen, and so restore the balance (quoted

* MS received 5 October 1959.

† Economic Adviser, Ministry of Power. All views expressed in the paper are those of the author personally, and do not necessarily reflect those of the Ministry of Power.

‡ "One of the most romantic aspects of the Elizabethan age was the wave of beards which suddenly swept across History and settled upon all the great men of the period" ("1066 and All That," 35th Ed, p. 58).

in *Smokeless Air*, Summer 1959, p. 302). One imagines that as more and more trees were planted they would stop more and more of the cars and lorries, reduce the atmospheric pollution, and so bring about a new equilibrium, possibly what some economists have called " the stationary state," something like the scene on many of our highways any summer week-end. This conclusion may not be wholly welcome to members of the IP, but at any rate we are unlikely to reach it for some time. Perhaps the practical moral from this kind of speculation is " Don't worry—it may never happen."

STANLEY JEVONS AND "THE COAL QUESTION"

Another who might well have taken heed of that motto was Stanley Jevons. Jevons taught economics at Owens College, Manchester, and he was, as far as the author knows, the first of the European energetic forecasters, though his focus was on Britain rather than on Europe as a whole. In 1865 he published " The Coal Question," on the thesis that " the coal we (British) happily possess in excellent quality and abundance is the mainspring of modern material civilization " but " we cannot long maintain our present rate of increase of consumption " (3½ per cent in 1865–66) because " rather more than a century of our present progress would exhaust our mines to the depth of 4000 feet, or 1500 feet deeper than our present deepest mine " so that " the cost of fuel must rise, perhaps within a lifetime, to a rate injurious to our commercial and manufacturing supremacy; and the conclusion is inevitable, that our present happy progressive condition is a thing of limited duration." This " inevitable conclusion " so distressed Jevons that he not only put on his title page the Latin text *non progredi est regredi* but also added the following variation from Adam Smith: " The progressive state is in reality the cheerful and the hearty state to all the different orders of the Society; the stationary is dull; the declining melancholy."

Jevons refused to find relief from these dull and melancholy prospects in the possibilities of increased fuel efficiency: " No one must suppose that coal thus saved is spared—it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms." Nor did salvation lie in importing coal from less exhausted lands: " While the export of coal is a vast and growing branch of our trade, a reversal of the trade, and a future return current of coal, is a commercial impossibility and absurdity."

What about substitutes for coal? Jevons pointed to the limited water-power resources of these islands. As for oil:

> " Petroleum has of late years become the matter of a most extensive trade, and has been found admirably adapted for use in marine steam-engine boilers. It is undoubtedly superior to coal for many purposes, and is capable of replacing it. But then, *what is petroleum but the essence of coal*, distilled from it by terrestrial or artificial heat? Its natural supply is far more limited and uncertain than that of coal, and an artificial supply can only be had by the distillation of some kind of coal at considerable cost. To extend the use of petroleum, then, is only a new way of pushing the consumption of coal. It is more likely to be an aggravation of the drain than a remedy."

Nor had Jevons any time for those who might hope that the future would reveal new sources of energy. In " The Coal Question " he recalled that " the popular scientific writer, Dr Lardner," had in 1840 suggested that before our coalfields were exhausted " other and more powerful mechanical agents will supersede the use of coal. Philosophy already directs her finger at sources of inexhaustible power in the phenomena of electricity and magnetism." Dr Lardner had thought " that we are on the eve of mechanical discoveries still greater than any which have yet appeared, and that the steam-engine itself, with the gigantic powers conferred upon it by the immortal Watt, will dwindle into insignificance in comparison with the energies of nature which are still to be revealed." Jevons commented: " Such high-sounding phrases would mislead no scientific men at the present day," and added in the margin of a new edition he was preparing at the time of his death—he lost his life in a bathing accident in 1882, at the age of 47—the pencilled note " They are worthy only of a savant who proved that a steam-vessel could not cross the Atlantic."

From the standpoint of to-day it is all too easy to suggest that perhaps Professor Jevons' melancholy findings were no less worthy of that savant than were Dr Lardner's great expectations. And it is all too easy to misrepresent the balance of Jevons' book—which is worth reading as a piece of logic in its own right—when one is simplifying his conclusions. Nevertheless, it stands as an awful warning to energy prognosticators: this first major essay in Europe's energetic forecasting was not a very happy one. Incidentally, although the author would not dare to list the instances to members of the IP, who know them far better than he does, there are, of course, many parallels to Jevons' coal forecasts, in estimates of world oil reserves. The author remembers that, years ago, world oil reserves were always going to be exhausted in the next generation—though there were always dissident voices, too, which now seem to have prevailed.

Jevons' forecasts in " The Coal Question " certainly caused a stir 90 years ago. As Dr Tugendhat recalled in his recent broadcast on " The Fossilized Fuel In-

dustries," Mr Gladstone, then Chancellor of the Exchequer, brought the approaching exhaustion of Britain's coal reserves into his 1866 budget speech; it seemed to him so critical a national problem that we ought to reduce the national debt as quickly as possible.* But whatever Mr Gladstone said in 1866, the passing years brought the development of new coalfields, great increases in fuel efficiency, a rapid growth in oil production—and a marked reduction in the rate of increase of energy consumption. Jevons' "coal question" faded away with the old century. Between the wars "the coal question" meant something quite different: how to find markets for all the coal that our mines produced, and provide employment for all the men who looked to them for a living.

APPREHENSIONS RENEWED

The post-war decade 1945–55 was quite different again. During those years of reconstruction and rapid economic expansion, energy consumption increased fast, and demand outran supplies, sometimes, as in the U.K. in 1947, with serious checks to industrial output. This situation, logically or not, revived the sort of apprehension about the long-run outlook which had troubled Jevons 80 years earlier. Faced with current shortages, people were driven to thinking on these lines: enormously increased quantities of energy will be required if national economies continue to expand at their present rates; areas such as Western Europe, which have traditionally been self-sufficient, with cheap and ample energy supplies, will have to exploit their higher-cost sources, and will become increasingly dependent on finding and paying for imports of energy; there may be intractable shortages and increasing costs, bringing the danger of a brake to progress and to rising standards of living, and adding to balance of payments difficulties; apart from all that, increasing dependence on imported basic supplies is unwelcome in an insecure world—particularly when the increased supplies are drawn from politically unstable areas of the globe.

Western Europe is probably the most vulnerable part of the world in the face of these dangers. But the present wave of energetic forecasting seems to have begun in the U.S.A. American concern at the post-war change from being a net exporter to being a net importer of raw materials and of energy led to the establishment of the President's Materials Policy Commission, under the chairmanship of William S. Paley. In five volumes and 70 recommendations the Paley Commission listed "the actions which, in its judgment, will best assure the mounting supplies of materials and energy which our economic progress and security will require in the next quarter century" ("Resources for Freedom," Volume III: "The Outlook for Energy Sources." A Report by the President's Materials Policy Commission: Letter of Transmittal by the President, 1 July 1952). They surveyed energy prospects for Western Europe also, and found that there had been only a small increase in energy consumption between 1913 and 1938; by contrast (they found) there was an increase of 20 per cent between 1938 and 1950; they forecast a further increase of 50 per cent in requirements between 1950 and 1975, which, given the prospective increase of European coal production costs, "in the absence of interruption from political developments," should be met principally by oil supplies from the Middle East. Thus the year 1975 came to be accepted as a suitable date for long-term energy forecasting—a quarter-century on from Paley's base year, 1950.

Meanwhile, another contribution to even longer-term energy forecasting was being made by Palmer Putnam, Consultant of the United States Atomic Energy Commission, who had been requested "to make a study of the maximum plausible world demands for energy over the next 50 to 100 years—as background for the Commission's consideration of the economic and public policy related to the development and use of machines for deriving electrical power from nuclear fuels." Mr Putnam published his findings, "Energy in the Future," in 1954. His approach to estimating maximum plausible energy consumption was to forecast maximum plausible world populations, and apply to those figures maximum plausible energy consumption per head. He estimated that world population rose from 1 million in the year 10,000 B.C. to 275 millions in A.D. 1 but was still only 285 millions in A.D. 1000. In A.D. 1550 it was 420 millions, but had risen to 1093 millions by 1850. Only 58 years later, in 1908, it had reached 1626 millions, in 1936 2076 millions, and by 1950, 2411 millions. Thus, despite two world wars, immensely destructive of human life, population grew as much between 1908 and 1950—a period within the lifetime of many people present to-day—as it did between A.D. 1 and 1850. From this rapidly increasing rate of growth Mr Putnam estimated a world population of 3700 millions in the year 2000, rising to 6300 millions in A.D. 2050.

Such a large population, he conceded, might "never come into being," but if it did it would not be based on "illiterate subsistence farming" (as most of the world's population at present is) but on "literate industrial–urban–farm patterns" and "would inevitably be characterized by higher average demands *per capita* for energy than those of to-day" ("Energy in the Future," pp. 69–70). Therefore a great increase in world population was not plausible without a great increase in demand for energy; to forecast the maxi-

* Hansard, 3 May 1866, Columns 399–403.

mum plausible world demand for energy in the future, Mr Putnam was driven to combine a large increase of population with a large and progressive rise of energy consumption per head. Even after making allowance for increased efficiency in the use of energy, he concluded that, from a total world energy consumption of 0·009 Q in 1950, world needs would rise to 2·2 Q in 2050. Q is a device for avoiding astronomical noughts; it is defined as one million million million British thermal units. A British thermal unit is a small quantity of heat, but multiplied a million million million times it becames a lot of heat—equivalent, in fact, to that in 38,000 million tons of coal. Mr Putnam calculated that, on his assumptions, the world would have used up something between 11 and 22 Q of energy between A.D. 1950 and 2000, and that by the year 2050 this cumulative total would have risen to something between 72 and 487 Q. Against these demand figures he estimated that world resources of fossil fuels, " recoverable substantially at present costs by present methods," amounted to no more than 27·2 Q. He concluded that " if present trends continue in population growth, in demand *per capita* for energy output as measured at the point of end-use, and in preference for fluid fuels and for electrical energy, then the real unit costs of energy from the harder-to-win and poorer-rank coal that remains, already rising in Europe as well as here, will cause a strong demand for new sources of energy sooner than many had realized —a demand that may become insistent by A.D. 1975 " (" Energy in the Future," pp. 169–70).

EUROPEAN STUDIES

The Paley Commission in 1952 and Palmer Putnam in 1954 thus stressed the rising energy needs of Europe and prospective stringencies by 1975, but their observations were, of course, incidental to the consideration of problems facing the U.S.A. The Organization for European Economic Co-operation now embarked on major studies of the general energy problems facing Western European. In December 1953 its Secretary-General had submitted to the governing Council a memorandum noting the rising cost of fuel and power, stressing the dangers this might present to economic progress in Europe, and suggesting possible solutions. The Council invited Louis Armand, Chairman of the French Railways Board, to make a further study of these problems. In the light of his report,* which emphasized the importance of cheap and abundant energy supplies as a key to progress, and proposed the establishment of an OEEC " Fuel and Power Economics Committee," the OEEC Council decided to appoint a group of experts to formulate energy balance-sheets and forecasts for Western Europe, to examine the chief problems, particularly economic and financial, and to make recommendations. This was the origin of the OEEC Commission for Energy, under the chairmanship of Sir Harold Hartley.

The Hartley Commission

The Hartley Commission, and the OEEC Secretariat who served them, did a vast amount of work on forecasting long-run energy demand and supply, and received much information and opinion from member countries, and from several of the major oil companies. In May 1956 their report was published, under the title: " Europe's Growing Needs of Energy: How Can They Be Met? "

The Commission used what they described as four independent means of forecasting Western Europe's energy needs:

> (1) Projections by the OEEC Secretariat of general economic progress in Western Europe, and of the total energy consumption which might be associated with it.
>
> (2) Forecasts by the Secretariat of future energy consumption in the major industries and in households throughout Western Europe.
>
> (3) Country-wise forecasts of energy use, made by the individual members of the Commission for their own and neighbouring countries.
>
> (4) Forecasts of the total energy requirements of Western Europe made available to the Commission by several of the major oil companies.

The Hartley Commission thought the results of these four diverse approaches were in sufficiently close agreement to enable them to forecast total Western European primary energy demand (on the definitions they used) as within the range of 820–860 million tons of coal equivalent in 1960, and 1100–1300 million tons in 1975, against actual consumptions of 730 million tons in 1955, and 583 million tons in 1950. This meant a doubling of energy consumption between 1950 and 1975—twice the increase which the Paley Commission had envisaged in 1952 for Western Europe.

Against these prospective energy demands, the Commission forecast Western European primary energy production (excluding nuclear power) at 645 million tons of coal equivalent in 1960 and 755 million tons in 1975, against 584 million tons in 1955 and 513 million tons in 1950. Comparing these forecasts of indigenous production with the mean of their demand estimates, they found a " gap " of 195 million tons of coal equivalent in 1960 and 445 million tons in 1975, against 146 million tons in 1955 and 70 million tons in 1950.

The Hartley Commission's recommendation

* " Some Aspects of the European Energy Problem," June 1955.

centred on the problems which they thought were raised by this rapidly growing "gap." In 1955, they found, it had been closed by a net import of 29 million tons of coal and 84 million tons (117 million tons in coal equivalent) of oil, at a total cost of $1900 million. If the forecast "gap" for 1975 were to be closed by imports the cost would amount to $5000 million, even at 1956 prices of coal and oil, both of which, they considered, were certain to rise. Such large energy imports would present serious balance of payments problems, give rise to anxiety about the security of energy supplies when so large a proportion must come from Middle East oil, and raise physical difficulties of transporting these large quantities of oil to Europe. There was therefore an urgent need for Western Europe to expand its own production of energy, and to foster greater efficiency in fuel use.

How was such an increase in Western European energy production to be achieved? The Commission took the view that the maximum contribution which nuclear power stations could be expected to provide by 1975 was 80 million tons of coal equivalent, leaving a "gap" of 365 million tons—just two and a half times the 1955 "gap." They stressed the need to search more intensively for oil and natural gas, and to harness still more hydro-power. But their estimates already envisaged doubling hydro-power supply, and quadrupling oil and natural gas output in Western Europe during 1955–75, so that they evidently hesitated to include in their forecasts still further increases from such extra efforts.

The main hope for reducing the European energy "gap" must, in the Hartley Commission's view, lie in expanding coal output. They stressed the need for more investment in the mines, for improving mining methods, and for making the coal industry more attractive as a career.

Because they foresaw a long-run problem of energy shortage, the Hartley Commission recommended "the formation of a new Committee of individuals selected for their experience in the field of energy" to keep under review energy production, consumption, imports, exports, prices, and investment, and to make proposals for any necessary action. In the light of the Hartley Report, the Council of OEEC decided in November 1956 to create an Energy Advisory Commission.

The Robinson Commission

The new Commission, under the chairmanship of Professor Austin Robinson, met in July 1957, and began the task of reassessing the long-run energy outlook for Western Europe, on the basis of new information which had become available since the Hartley report was produced. The Robinson Commission followed much the same methods as those used by their predecessors in forecasting energy demand and supply—and reached much the same statistical conclusions.*

In forecasting demand, the Robinson, like the Hartley Commission, again asked the OEEC Secretariat for projections of the economic progress of Western Europe as a whole, and for their translation both into total prospective energy use and into consumption by each of the principal using sectors. The Secretariat's conclusions about prospective changes by 1965 and 1975 from the levels of 1955 were summarized by the Robinson Commission as in Table I below.

TABLE I

OEEC Secretariat's Estimates of Changes Relating to Western Europe's Energy Demand, 1955, 1965, and 1975

	Percentages		
	1955	1965	1975
Gross National Product	100	136	183
Industrial production	100	147	208
Final energy demand: *			
Iron and steel industry	100	150	206
Other industries	100	130	167
Railways	100	84	58
Other transport	100	160	228
Domestic, etc	100	115	133
Ocean bunkers	100	132	181
All sectors	100	126	157
Corresponding primary energy demand *	100	130	172

(Source: Report of Energy Advisory Commission, Tables 6 and 7.)

* *Final* energy demand here means the total heat content of all the various types of energy as actually delivered to consumers; *primary* energy demand means the heat content of each of the primary forms—coal, lignite, oil, natural gas, and nuclear fuel—used for meeting the final energy demand, except for hydro-power, which is converted not to the energy content of the falling water used to generate it, but to the heat content of the coal which would have been required to generate the same amount of electricity; as shown in Annex I to the Robinson Report, this exception does not significantly alter these present comparisons.

Again, like the Hartley Commission, the Robinson Commission mobilized the experience and contacts of its members to obtain forecasts of energy demand for individual countries. Estimates for Belgium, France, Germany, Italy, Luxembourg, and the Netherlands were, however, supplied by the High Authority of the European Coal and Steel Community. The country-wise estimates were aggregated and summarized by the Commission as in Table II.

Finally, like their predecessors, the Robinson Commission sought the advice of some of the major oil companies on the outlook for energy demand in Western Europe. These opinions covered a certain

* The Energy Advisory Commission's Report was published in January 1960 under the title "Towards a New Energy Pattern in Europe."

range, which the Commission presented as 135–139 for 1965 and 171–185 for 1975 on the base 1955 = 100.

The Report presented these three sets of estimates

TABLE II

Aggregate of Estimated Changes in Energy Demand of Western European Countries, 1955, 1965, and 1975

	Percentages		
	1955	1965	1975
Final energy demand:			
Iron and steel industry	100	142	183
Other industries	100	137	176
Railways	100	83	70
Other transport	100	170	225
Domestic, etc	100	117	127
Ocean bunkers	100	132	181
All sectors	100	129	155
Corresponding primary energy demand	100	134	167

(Source: Report of Energy Advisory Commission, Tables 9 and 10.)

together with their translation into quantities of primary energy, expressed in coal equivalent, as in Table III.

TABLE III

Comparison of Three Estimates of OEEC Primary Energy Consumption, 1955, 1965, and 1975

	Index			Million metric tons of coal equivalent		
	1955	1965	1975	1955	1965	1975
Secretariat's estimate	100	130	172	777	1010	1340
Country-wise estimate	100	134	167	777	1040	1300
Oil companies' estimates	100	133–139	171–185	777	1035–1080	1330–1435

(Source: Report of Energy Advisory Commission, Table 12.)

Reviewing these three demand forecasts, the Robinson Commission noted that the Secretariat's and the country-wise estimates were relatively close, and this seemed to them " to suggest that the probable errors in our forecasts stem from the sort of mistakes of general optimism or pessimism that are likely to affect at a given moment all who attempt such forecasts, rather than from errors that may be involved in particular approaches to the problem " (Report, paragraph 43). The oil companies' estimates were on average somewhat higher than the Secretariat's and the country-wise forecasts, which prompted the Commission to comment: " It seems clear that some at least of the oil companies take a rather more optimistic view of the potential expansion of the European energy market " (Report, paragraph 44).

In the light of these three estimates of energy consumption in recent years, and of their own expectations about the general prospects for the economy of Western Europe, the Commission themselves adopted a range of forecasts which covered all three estimates except the top of the oil companies' bands, and centred close to the Secretariat's estimates. These new forecasts were very similar to what can be interpolated for 1965 between the Hartley Commission's forecasts for 1960 and 1975, and were somewhat higher than Hartley's for 1975. The comparison is given in Table IV below.

TABLE IV

Comparison of Hartley and Robinson Commissions' Estimates of OEEC Energy Demand, 1955, 1965, and 1975

	Percentages			Million metric tons of coal equivalent		
	1955	1965	1975	1955	1965	1975
Hartley Report: *						
Upper estimate	100	136	175	777	1060	1360
Mean estimate	100	130	162	777	1010	1260
Lower estimate	100	124	149	777	960	1160
Robinson Report:						
Upper estimate	100	135	183	777	1050	1425
Mean estimate	100	130	171	777	1010	1325
Lower estimate	100	125	158	777	970	1225

(Source: Report of Energy Advisory Commission, Tables 13 and 14.)

* These are not the actual figures which appear in the Hartley Report, because: (*a*) the Hartley Commission gave forecasts for 1960 and 1975, not 1965 and 1975—the 1965 figures given here are interpolated by the Robinson Commission; (*b*) the Hartley Report figure for 1955 has been replaced by the later estimate used by the Robinson Commission; (*c*) the Hartley Commission's forecasts have been adjusted to the same definition of demand as used by the Robinson Commission (*e.g.* ocean bunkers have been added).

From forecasting a growing energy demand the Hartley Commission had gone on to consider what were the prospective supplies from indigenous sources, and how they might be increased in order to reduce the " gap "—an approach reflected in the title of their Report. The Robinson Commission moved on from their similar forecast of growing energy demand in a different way: they considered first, within their estimate of total consumption, how far it was possible to forecast demand for particular forms of energy.

This they recognized as peculiarly difficult. It is worth quoting the relevant paragraphs of their Report in full. They are as follows:

> " It must be emphasized that the difficulties of forecasting the consumption of individual competing sources of energy are so great that the most that can be attempted is to indicate wide limits of possibility. While the consumption of energy in total increases in a reasonably predictable relation to gross national product and to

industrial production, the consumption of individual forms of energy must depend on the relative prices, as well as the technical advantages and conveniences, of particular fuels, and thus ultimately on their costs of production. In the case of the traditional fuels, such as coal, oil, and hydro-electricity, for which there is a long experience of their competitive substitution for each other, it is not impossible to make use of past trends. But for a number of newer sources of energy, such as natural gas and nuclear energy, it is necessary to make estimates which represent to a much greater extent judgments of possible rates of technical development, and which are necessarily much more speculative.

"There are certain demands for energy that are rather rigidly specific to certain determined primary sources of energy. Thus the demand for coal for carbonization or for oil for use in internal combustion engines for transport purposes is rather rigidly specific. The choice between coal, lignite, natural gas, oil, or (so far as the considerations are purely economic) nuclear fuels for the generation of electricity is by no means rigid, and consumption will be attracted to one fuel or another in accordance with variations of the relative prices and the relative convenience and security of using them.

"A large part of the aggregate demand for energy in general is transferable from one energy source to another over a period as long as that between the present and 1975 in response to relatively small and almost unpredictable variations of relative prices. Over a short period the pattern of consumption is in some degree stabilized not only by the existing preferences of consumers but also by the existing types of installations and equipment for the use of particular fuels But over a period of 16 years many of these will become due for renewal, and new equipment will take account of new expectations of future relative prices" (Report of Energy Advisory Commission, paragraphs 51–3).

The Robinson Commission went on to consider how far, in the light of these major uncertainties, they could forecast the pattern in which the demand for energy would be met in the future. They stressed the importance of cost and price in an increasingly competitive world; while the scale on which lignite, natural gas, and hydro-power would be produced in Western Europe would be determined primarily by their supply possibilities (because costs would in the period under review be less than the relevant costs of their competitors) the place of Western European coal in competition with imported coal or imported oil would depend mainly on its cost of supply. By implication, they assumed that the future scale of crude oil output in Western Europe would be determined primarily by its supply possibilities. They noted that the search had "recently been intensified" but commented: "Forecasts of crude oil production in Western Europe are very difficult to make, since not only are the reserves uncertain but also their exploitation is likely to form a relatively small part of the world-wide activities of the international oil companies" (Report, paragraphs 84–5).

The Commission felt able to predict long-run demand for electricity with some confidence, on the basis of clear and persistent trends in the past, and their own assumptions about future economic progress; by contrast, when they came to forecast how much of that demand would be met from nuclear rather than conventional sources, they found the range of uncertainties so wide and so formidable that, although present programmes gave some indication of nuclear-electricity production prospects in 1965, "We find ourselves unable to present anything but a wide range of possibilities for 1975. Different members of the Commission hold widely different views as to what is possible and probable" (Report, paragraph 114).

Imported natural gas was another field with great potentialities and great uncertainties:

> "There are very great possibilities of developments of this if some of the technical and economic problems of transportation can be satisfactorily overcome. If, as is not unlikely, it proves possible before 1975 to integrate the natural gas of the Saharan field into a distribution system of Western Europe, either by solution of the problems of shipment by sea or by pipeline, there are very large quantities of primary energy capable of being utilized. Any estimate must be of the nature of guess-work. . . ." (Report, paragraph 132).

By contrast, the size of the balancing items in the energy balance sheet—imported oil and coal—would be determined (like that of indigenous coal) primarily by their competitive power.

The Robinson Commission's picture of Western Europe's energy budget in 1965 and 1975 is summarized in Table V below.

The Robinson and Hartley Reports Compared

The author would like now to present a table comparing the forecasts of the Robinson Commission with those of (or which can be derived from) the Hartley Report. This comparison is given in Table VI below; it is simplified as far as seems feasible, but remains complex, because it is comparing two comparisons over time. The author feels inclined to utter some

TABLE V

OEEC Balance Sheets of Primary Energy, 1955, 1965, and 1975

	Million metric tons of coal equivalent		
	1955	1965	1975
Estimates of Total Demand for Primary Energy	777	970–1050	1225–1425
Mean of estimates	777	1010	1325
Potential Indigenous Supplies			
Coal	477	440–480	430–495
Lignite	30	45	60
Crude oil	13	30	50
Natural gas	7	25	50–60
Hydro-power	56	95	140
Nuclear energy *	—	15–20	30–90
Other fuels	20	20	20
Total	603	670–715	780–915
Mean of estimates	603	690	850
Potential Imported Supplies †			
Liquid fuels	146	260–310	380–500
Natural gas	—	5	10–75
Solid fuels	28	10–60	10–60
Total	174	275–375	400–635
Mean of estimates	174	325	515
Total Potential Supplies	777	945–1090	1180–1550
Mean of estimates	777	1015	1365

(Source: Report of Energy Advisory Commission, Table 31.)

* Although nuclear energy is shown under indigenous supplies, it should be noted that the greater part of the fuel will have to be imported.

† Excluding increases of stocks in 1955.

warning, in the manner of Lewis Carroll and Dennis Robertson.*

The comparison between the Hartley and Robinson forecasts may be summarized thus:

(1) Robinson's (mean) demand forecast is the same as Hartley's (interpolated) figure for 1965 and substantially higher for 1975.

(2) Robinson's forecasts of total indigenous supplies are somewhat less than Hartley's in both years, mainly because Robinson's higher forecasts for lignite, hydro-power, and natural gas do not fully offset their lower forecasts of coal production (and, in 1975, of nuclear energy).

(3) Consequently, Robinson's estimates of import requirements are in both years higher than Hartley's; this increase they expected to be met wholly by oil and natural gas imports—their estimates of coal imports are lower than Hartley's.

Thus Robinson expected Western Europe's energy consumption to be higher, some 15 years hence, than did Hartley, but indigenous coal production to be much lower, and the need for energy imports correspondingly greater. Paradoxically, however, it was the Hartley Commission which urged increased coal production as a means to solve what they regarded as the critical problem of the growing energy "gap"; the Robinson Commission envisaged a falling coal

TABLE VI

*Hartley * and Robinson Commissions' OEEC Primary Energy Balance Sheets, 1955, 1965, and 1975*

	Million metric tons of coal equivalent				
	1955	1965 †		1975 †	
		Hartley *	Robinson	Hartley *	Robinson
Total demand	777	1010	1010	1260	1325
OEEC production:					
Coal	477	520	460	520	465
Lignite	30	35	45	35	60
Hydro-power	56	90	95	130	140
Nuclear energy ‡	—	10	15	80	60
Crude oil	13	30	30	50	50
Natural gas	7	15	25	25	55
Other forms	20	20	20	20	20
Total	603	720	690	860	850
Potential imports:					
Liquid fuels	146 §	250	285	350	440
Natural gas	—	—	5	—	40
Solid fuels	28 §	40	35	50	35
Total	174	290	325	400	515
Total supplies	777	1010	1015	1260	1365

(Source: Report of Energy Advisory Commission, Table 31 and Annex 3.)

* The figures given for the Hartley Commission's forecasts are not those which appear in their Report: they are adjusted to give the same coverage as the Robinson Commission's forecasts, and the estimates used here for 1955; the Hartley Commission did not give forecasts for 1965—those shown here are interpolated between their estimates for 1960 and 1975.

† The mean figures of the forecasts are rounded to the nearest 5 million tons.

‡ Although nuclear energy is here shown under indigenous supplies, the greater part of the fuel will have to be imported.

§ Excluding increases of stocks.

output, and were not unduly dismayed by the prospect of still greater energy import needs.

How is this paradox explained? The author suggests five reasons:

(1) The Hartley Commission implicitly assumed that the real cost of increased indigenous coal production would be less than that of equivalent energy imports, and considered that greatly increased energy imports would present intolerable balance of payments problems. By contrast, Robinson noted the long-term tendency for coal costs to rise relative to those of other

* "Ahem!" said the Mouse, with an important air. "Are you all ready? This is the driest thing I know. Silence all round, if you please" ("Alice's Adventures in Wonderland," quoted by D. H. Robertson, "The Control of Industry," p. 1).

commodities, including oil, and took the view that Western Europe's increasing energy import bill would be supportable in the expanding economy with which such increasing energy demands would be associated.

(2) During the two years between the investigations of the Hartley and Robinson Commissions, the persistent wartime and post-war shortage of fuels disappeared as economic recession brought a check to rising energy demand; the immediate pressure for increased coal production, even at high cost, gave place to the problem of how to absorb available supplies. The main cause of this change was the industrial recession, which has little to do with the outlook for energy demand 15 years hence—so little, in fact, that Robinson's forecast for 1975 was, as noted previously, appreciably above Hartley's. Nevertheless, such striking changes, even if their direct effect is short-term only, do influence long-term forecasting, and (to quote the Robinson Commission again) tend to produce " the sort of mistakes of general optimism or pessimism that are likely to affect at a given moment all who attempt such forecasts " (Report, paragraph 43).

(3) This change from immediate shortage to energy surplus partly explains another difference between Robinson and Hartley. The Hartley Commission tended to aggregate energy demand, and set against this total demand an aggregate of total energy supplies, with the implication that, over most fields of use, the " gap " could as well be filled by one form of energy as another. The Robinson Commission (as has been shown) in fact did the same statistical exercises in aggregation, but in their conclusions were more influenced by the consideration that, to a large extent, energy demand is more or less specific to particular forms of energy, so that it would be unrealistic to advocate the closing of a growing " gap " by any one form of energy.

(4) Apart from this general consideration, Robinson must have hesitated to endorse Hartley's recommendation that the growing " gap " should be met mainly by increased coal production, in the light of the facts that between 1955 and 1959 the switch in demand from coal to oil had accelerated, and that, in consequence, some of the major coal producers were known to be reducing their long-term production plans.

(5) Finally, estimates of world energy resources and potential supplies have increased since 1955. The Hartley Commission were particularly concerned about Western Europe's increasing dependence upon Middle East oil supplies. But Western Europe's own oil output goes on rising, and recent developments, especially in Africa, may radically alter the long-term outlook—so much so that, according to a report published in the *Financial Times* of 28 May 1959, the six Common Market countries now forecast that the equivalent of the whole of their energy import needs may by 1975 be available from Saharan oil and natural gas production. The forecasts are, in million metric tons of coal equivalent, a total ECSC demand of 676 and an indigenous supply of 470, leaving a deficit of 206, against which Saharan production might be 150 of oil and 60 of natural gas. This is evidently speculative—both on supply and transport possibilities. But in his recent articles on " Europe and the Oil Industry " in *The Times*, Dr Tugendhat wrote: " Many people on the Continent now forecast that within the next five years oil and gas production on the Continent and in the Sahara will exceed 100 million tons and top 125 million tons within ten years." (Translated into coal equivalent on the Robinson Commission's basis, these figures are 140 and 175.) " Perhaps," he added, " this may sound too optimistic, but we should also beware of facile pessimism." The Hartley Commission were disturbed not only about future oil availability at source but also about its rising foreign exchange cost to Europe: the potential increase of world supplies, and in particular the prospective development of Saharan oil, within the French Community must, in the eyes of the Robinson Commission, abate both problems.

For these reasons, while the Hartley Commission pressed for increased coal production, the Robinson Commission stressed rather that in the energy policies of Western Europe " the paramount consideration should in our view be an adequate supply of energy at the lowest possible economic cost, with freedom of choice to the consumer " (Report, paragraph 171).

IS ENERGETIC FORECASTING A GOOD THING?

The striking diversity of the conclusions for policy drawn from two detailed energy forecasting exercises made within two years and yielding similar statistical results must raise the question whether such major studies are worthwhile.

It can be argued, on this evidence, that elaborate long-term energy forecasts are time-wasting and indeed positively dangerous, in that, based on such studies, wrong long-term decisions, for instance on the scale of investment in Western Europe's coal production, may be taken—invalidated in the event, and meanwhile called in question by later long-term forecasts.

In the author's judgment, intelligent long-term energy forecasts *are* worthwhile—*provided that people who use them as the basis for policy can be made and kept fully aware of the inherent limitations of all such*

exercises. It seems both interesting and important to guess where economic progress will have taken us 15 or 20 years hence, what the main energy problems then will be, and what (if any) bearing these guesses have on decisions which must be taken now. If long-term forecasts are not made on the basis of careful study they will still be made—but made "off the cuff." Any decisions based on such guesses are likely to be worse than decisions based on detailed (and fully understood) energy forecasts.

But this qualification is of crucial importance: the inherent limitations of even the most intelligent of forecasts must be recognized by all who seek their guidance in taking decisions. The bottle must be clearly and indelibly labelled and the label must be read and understood; otherwise, the results of application may be serious. It is worth briefly reviewing the nature of these limitations in energy forecasting.

First, there is the large group which arises from the uncertainties of the future. Estimates of total energy demand, for instance, are inevitably geared to assumptions about the future rate of economic progress, and therefore about invention, incentive, enterprise, population, labour force, world conditions, and so on. And when assumptions have been made about the rate of economic progress there are further uncertainties about the level of total energy demand likely to be associated with it: here the future pattern of economic activity is relevant—what changes will occur in the heavy fuel-using industries in particular—and so are prospective changes in fuel efficiency and patterns of energy consumption. One must recognize that the future may hold large but unpredictable changes in methods of energy use. Here future changes of energy prices are relevant. In a rapidly changing world, energy price relations may greatly alter within a decade. And here also, of course, politics come in: will governments intervene, and to what extent, either by import restrictions or by taxes to protect indigenous producers?

Guessing future price relations raises questions of energy supplies—and also still more uncertainties. On the supply side there are formidable uncertainties about the future output and price of each source of energy. What will be the future marginal costs of Western European coal supplies? Will more oil suppliers seek major outlets in Western Europe? What new oil reserves will be discovered, when will they be exploited, and at what cost? What are the prospects for natural gas, both indigenous and imported? How favourable will the costs of nuclear power turn out to be? Each of these questions enfolds still more uncertainties, like a Chinese puzzle. In forecasting, it is necessary to make some assumptions, express or implied, about each of them. The margins of error in all these assumptions, multiplied in the process, inevitably mean a wide degree of uncertainty in the final estimates—so wide that, perhaps, one should call them "exploratory calculations," to use a term of E. F. Schumacher's, rather than forecasts.

A second type of limitation arises from problems of presentation. The formal homogeneity of energy statistics conceals a diversity which can only be made manageable in the text and tables of a report by using some conventions. This is a statisticians' happy hunting ground, where the author would hesitate to tread. Two examples will be mentioned, however.

One is the problem of conversion factors to be used in aggregating different forms of energy. The OEEC forecasts take one ton of oil as equivalent to 1·4 tons of coal, because this is the approximate thermal equivalent ratio of crude oil to coal. The Ministry of Power's statistics take one ton of oil as equivalent to 1·7 tons of coal, because this is closer to the thermal equivalent ratio of petroleum products to coal. Again, the OEEC statistics convert hydro-electricity into primary energy, expressed as million tons of coal equivalent, on the basis of the amount of coal which would be needed at a modern coal-fired power station to generate the same amount of power, *i.e.* 1 kilowatt hour is taken as equivalent to 0·4 kg of coal. But it would be more logical, if less convenient, to convert hydro-power into primary energy on the basis of the energy in the falling water used to generate the electricity. Because modern hydro-stations have an efficiency of 70 per cent or more, this would mean converting 1 kilowatt hour of hydro-electricity as equivalent to 0·2 kg or less of coal. Which of such conversion factors is used is partly a matter of taste, and partly a matter of the circumstances of the particular exercise. Annex I of the Robinson Report (as noted previously) shows that the choice made no material difference to their conclusions, so in this case, as W. S. Gilbert might have said, "it really doesn't matter"; but in other forecasting exercises it might make significant differences, at any rate to the appearance of the results. It is therefore important to show clearly the conversion factors which have been used.

The other example of presentation problem is the question of the stage at which demand for energy is to be measured. The OEEC studies present statistics of primary energy, and also of final demand for energy, *i.e.* energy as delivered, in whatever form, to consumers. But it would also be logical to go further, and compare the useful energy available to consumers at different times, *i.e.*, the energy delivered, less losses at the utilization stage. To make such comparisons would correct the impression, for instance, that the scale of operations of the railways was drastically contracting with the switch from the steam to the electric locomotive, the former with a very low, and the latter with a very high utilization efficiency. The difficulty about making comparisons of useful energy is the fact that utilization efficiencies differ greatly between one field of application and another; an average utilization efficiency in such conditions is a

rather meaningless convention. Again, however, it does not, in the author's view, matter much in practice if the forecasts as presented go no further than the "energy delivered" stage—providing that the limitations of these comparisons are understood, and providing also, it is suggested, that the forecasters themselves give some serious consideration to what their forecasts may imply for the future level of useful energy consumption.

But however carefully the limitations in energy forecasting exercises are stated in the original, there will always be the danger that they will be neglected in the course of successive interpretations of the Report. The following is an imaginary (but not, it is thought, wholly improbable) example of a chain of quotation from the Robinson Report:

> Robinson Report:
> "It would not be unreasonable to suppose that the oil production in the Sahara may reach . . somewhere between 60 and 100 million tons (about 90 to 140 million tons of coal equivalent) by 1975" (paragraph 130).
>
> Mr A, interpreting Robinson:
> "The Robinson Commission envisage Saharan oil production as rising up to 140 million tons in terms of coal equivalent by 1975."
>
> Mr B, interpreting Mr A:
> "The Saharan oil production figure for 1975 is 140 million tons."
>
> Mr C, trying to interpret Mr B:
> "As is well known, Saharan oil output in 1975 will be 140 million tons, *i.e.* some 200 million tons of coal equivalent."

No answer to this is known except constant vigilance. In an imperfect world one must recognize that this tendency is itself a limitation to the value of forecasting.

Still another limitation of long-term forecasts is their comparative irrelevance to what is likely to happen in the short term. Alfred Marshall inscribed on the title page of his "Principles of Economics" the text *Natura non facit saltum*, presumably implying that economic progress, too, does not go by jumps. But it certainly goes by a series of wriggles, so that the best forecasts of the level of national prosperity (and of energy use) in 15 or 20 years' time throw no light on the prospects for next year or the year after that. This does not mean that short-term forecasts are not worthwhile; merely that long-term forecasts cannot be used as substitutes for them. It does seem, however, that past forecasts of a long-term rise in the demand for energy may have, for instance, encouraged Western European coal consumers to bind themselves in coal import contracts for some years ahead, on the basis that there would be a shortage each year. The moral seems to be not to take short-term decisions on the basis of long-term forecasts—conversely, of course, long-term decisions should not be taken on the basis of short-term forecasts. A more sophisticated conclusion would be not to take major and irrevocable decisions before one must—the long-term outlook may change meanwhile. You may know the allegedly true story of the famous conductor who was walking in London and wearing a heavy overcoat, on a day that grew increasingly warm. He presently called a taxi, threw the coat inside, and said "Follow me—the weather may change." By postponing the decision he may have avoided a bad cold.

Finally, there is a limitation on long-term forecasting which, it is considered, arises from the fact that even forecasters are mortal human beings, who find difficulty in painting a picture of the situation 10 or 20 years hence, without putting in colours they see around them at present, or expect to see in the near future. I do not think that anyone, whether forecasting the results of horse-racing, football matches, economic progress, or energy demand, can be wholly immune from what the Robinson Commission have called (to quote the passage for the third time) "the sort of mistakes of general optimism or pessimism that are likely to affect at a given moment all who attempt such forecasts." Thus it is believed that, just as the great fuel shortages still current in 1955, and the great coal surpluses of 1958, must have influenced the respective conclusions of Hartley and Robinson about the energy problems of 1975—and, as suggested previously, partly explain the differences between them—changes in the general energy outlook during the next year or two would affect the conclusions of any new long-term forecast which might now be set in train. This, of course, is not to suggest that long-term forecasting is so subjective as to be useless. It is merely a warning that, in using the results of such exercises, we neglect the facts of life at our peril.

The conclusions can be summarized briefly. It is believed that intelligent long-term energetic forecasting is a useful exercise—providing that its limitations are clearly expressed and understood, and that mistaken interpretations from it are corrected as opportunity serves. It is hoped that such long-term forecasts will not be made the basis for short-term decisions. And the author hopes also that, having since 1955 taken several ranging shots at 1975, we can leave that year alone for some time. To echo Messrs Sellar and Yeatman, this wave of energetic forecasting, if not one of the most romantic aspects of the neo-Elizabethan age, is certainly an interesting one, which has swept across Europe and settled upon the desks of some of the top people of the period. It would be a pity to sweep it off too quickly, by generating still another energetic wave too soon.

DISCUSSION

M. E. Hubbard (The British Petroleum Co. Ltd): Crystal gazing by a seer as articulate as Mr Chantler is a delight, and such a contrast to some of the dry discussions one hears so often on energy problems. May I congratulate him warmly not only on the content but also on the form of his paper.

I feel for him in his forecasting, because I had to do the same work for quite a number of years. But being rather more free to choose my premises, I always adopted that of never giving a figure for a date earlier than my expected date of retirement. Unfortunately the terms of reference of the Robinson Commission made it impossible for Mr Chantler to follow the same rule, so he took the wise precaution, at the end of his paper, of saying, in effect, that he recommends people not to read such forecasts.

I think I can safely say that the oil industry warmly welcomes the Robinson Report. It is valuable to us as guidance, but it is also particularly valuable in other countries, notably in the producing countries, as it explains some of the facts of life. There is not an unlimited demand for oil; further, if oil tries to compete too actively with coal, the Report shows that there may well be a reaction to its own detriment by way of fiscal protection for other forms of energy.

Analysing the Robinson Report from the objective angle of the oil industry itself, the rate of growth suggested as likely from 1955 to 1965 (taking the mean figures for oil) is of the order of 7 per cent per year, as against the 12 or 13 per cent on the average for the post-war years up till 1958. From 1965 to 1975, the rate suggested would drop to 4¼ per cent per year, on the average over the ten years. These sound like very big reductions in the rate of growth of the oil industry. If one puts the accent on the word "rate," this is true; but if one looks at it tonnagewise over the current ten years, the Robinson Report implies an increase of 10 million tons per year, each year, and in the following ten years, about 11 million tons per year, each year. I do not think that we in the oil industry should complain unduly about that, although we hope to do rather better. This leads to the one point in the Robinson Report that I do not quite follow. The Robinson Commission had three detailed forecasts before it—a Secretariat forecast, countrywise forecasts, and the oil industry's forecast. All three agreed remarkably closely, the oil industry's forecast being marginally higher than the others. Then the Commission, giving no explanation, adopted its own figures, which are measurably lower than the average of all those three basic forecasts. Taking the mean index for 1965, the average of the three basic forecasts is 134, but the Commission adopted 130 in their calculations. For 1975, much the same occurred, the mean of the basic estimates was 174, and the Commission adopted 170. In each case, there was a difference of four points. Why? No explanation is given in the report nor in Mr Chantler's paper. It may sound small, but these four points are equivalent to 30 million tons of coal equivalent, and 20 million tons of oil means a lot of capital expenditure.

Could Mr Chantler throw any light on this apparently arbitrary scaling-down of total energy demand by the Commission?

Philip Chantler: I agree that the Commission's estimates are four points lower, *i.e.* 3 per cent in 1965 and 2 per cent in 1975, than the average of the three forecasts submitted to them. It is difficult to expound briefly the process by which the Commission reached their own conclusions. They had a great deal of discussion over many months, and during that period the atmosphere was increasingly bear-ish: the Commission were inclined to be less buoyant about future demand than the average of the estimates prepared for them a few months earlier.

I do not think that a variation of 3 per cent in the forecast for 1965 is significant—and still less 2 per cent for 1975. The margin of error in all these forecasts is far greater than that; in my view no great weight should be attached to a variation of 30 million tons of coal equivalent in forecasts for 1975. I prefer to think in terms of wide ranges: the Robinson Report concluded that probable demand in 1975 would lie somewhere between 58 and 83 per cent above 1955.

O. F. Thompson (Shell International Petroleum Co. Ltd): We have a speaker tonight of such calibre that he poses a problem as to what should best be drawn out of him in the short time available to us. One aspect which I feel it would be of interest to get him to speak upon, and it is an aspect which he has not really covered in his most entertaining paper, is to what extent does he foresee the possibility of improving the tools of forecasting? In other words, what needs to be done in improving the scope and nature of our statistical equipment, and likewise the scope for improving the speed at which this data can be made available? There is also the question of knowing more about the habits of the consumer. It can be said that the habits of consumers are unpredictable. This may be so. But, as a case in point, if we consider the millions in this world who are living at sub-standard levels, it is a fact that their habits have been changing in a way that needs quite scientific analysis to perceive. It is this kind of analysis that can provide a tool for better judgment in forecasting.

Philip Chantler: I warmly agree with Mr Thompson that the more information we can obtain about the pattern of consumer behaviour, the better for this purpose; all too often one finds oneself making forecasts purely on the basis of hunch. Most long-range forecasting is extrapolation. The statistical tools used to-day are quite refined, but they are based mainly on past behaviour, and the big unknowns are the future changes. If one can make firm and sound assumptions, one can very often make a good forecast, because the statistical technique is fairly well developed. I have the greatest respect, for example, for the work which the OEEC secretariat, particularly their economics division, did for the Commission; it is expounded in annexes to the Report. But the baffling thing is the changes that may come along, and all one can do then, I suppose, is to try to make intelligent assessments, on the basis of experience, of what people are likely to do in different conditions. I see value in sample investigations of human behaviour in particular conditions, but they give limited guidance on how people are likely to behave in the future.

G. Chandler (Shell International Petroleum Co. Ltd): We have heard, presented with extreme modesty, and also with erudition and wit, a description of the birth and development of a very powerful weapon. Mr Chantler has spent a lot of time qualifying the worth of this weapon, and I am reminded (respectfully of course) of a small boy gleefully prodding a time bomb—a time bomb, because of the inevitable impact and importance

of the Robinson Report on public and private policy. Mr Chantler has been an accessory before, during, and after the fact, and I would have expected, in the light of his admirable paper and of the cautions that he has uttered to-night, that there would have been a preface of some kind to the Robinson Report saying, "Suspend belief all ye who enter here." But, in fact, we are confronted with no such thing; and here we have, in black and white, some very precise forecasts, on which inevitably certain decisions are going to be made.

Turning this into a question, I would like to ask the speaker what he, or rather what the Commission, expected to happen to this document? How did they expect it to make its impact? And why there was not some more emphatic *caveat* expressed for outside consumption about the very grave limitations which beset this whole exercise?

Philip Chantler: It is hard to answer Mr Chandler's question both briefly and honestly. I think it would have been difficult to have drafted a form of warning that would have been acceptable to all members of the Commission. My own sympathies are with Mr Chandler, but I think it was necessary to leave readers of the Commission's Report to draw some of the important conclusions for themselves.

S. Eadie (Shell International Petroleum Co. Ltd): I would like to ask the speaker if, in the course of his work with the Commission, any question arose on the relationship of one of the most important economic indicators, that of industrial production, with energy. It seems to me that in recent years the relationship between industrial production and energy, in Europe particularly, has changed so markedly that it might be worthy of some comment.

Philip Chantler: This question was discussed at great length by the Commission with the secretariat of OEEC, and those discussions are to some extent reflected in Annex 2 of the Report. The pattern of industrial production alters over time very appreciably, and so does the coefficient of energy consumption. This has been very markedly so in the U.K. There was a different relation during 1920–39 between energy consumption and industrial production from that during 1945–55, and again during 1955 and to 1960. Tables I and II of my paper show that the increase of final energy demand is expected to vary greatly between the different main sectors of the economy. Where a country is expected to develop mainly in the heavy fuel-using industries (cement and iron and steel, for instance), there will be an entirely different coefficient of fuel use from conditions where more expansion is expected in, say, agriculture. Forecasts of energy demand must therefore be related to the expected future pattern of the economy.

M. G. Graham (Shell International Petroleum Co. Ltd): The speaker's wonderfully insouciant approach to the presentation of his material has prompted me to consider—when he said that much of the forecasting one is going to do would be wrong, but if one does not do it somebody else is going to have to do it on the back of an envelope—whether we should not do an exercise which compares the standard error in the past for a series of forecasts put down on the back of an envelope with the standard error in forecasts made by the experts and see what the difference in the errors might be in terms of cost in under- or over-investing in capital equipment, then see whether the cost of employing the forecasters is more or less than this, and perhaps act accordingly.

I was interested in his earlier remarks about the nature of developments in science and industry which makes it awfully difficult to spot which horses are going to come through at the next stage in the race. And his quotations from Jevons in that context were extremely interesting. You never can tell. There are cases where newcomers have a very short innings, such as electric traction for road transport, whereas one might have thought that electricity at that stage was going to be in for a long time. Nevertheless, if one takes the historical approach to basic primary fuels, perhaps one gets development going in broad phases. Mr Chantler suggested that we should lift up our eyes to the hills, and not grub around in the foothills. We should therefore try to see what these phases are. One has to do it on hunch, but it seems to me that perhaps some of those who were connected with looking at how the future would go at the time of the Hartley Report were looking one stage too far ahead; they were looking at the slope of the hill, as it were, one terrace farther up than we have yet reached. The broad present sweep of events is taking us into the age of oil, not the age of the atom, which is one stage farther ahead; whereas some of those responsible for decisions in the U.K. have lumped them together and moved forward too far.

May I ask Mr Chantler what he thinks about one aspect of the forecaster's tools. We have clearly reached the stage now when we need a much closer look at end-use analysis if we are to improve our techniques. The basic statistics on which one does this are clearly ineffective in many areas. Not everywhere—in the U.K. they are better than almost anywhere; but I wonder what Mr Chantler thought, in the light of his going back to Pakistan and many other different places, as to what is the best method nationally, or internationally, of improving this kind of statistics; whether existing bodies are satisfactory and, if not, what sort of new bodies would be required.

Philip Chantler: My first reaction is that the biggest improvement I can suggest for international energy statistics would be effective standardization, especially in equivalents and conversion factors. It is maddening, in preparing statistics for different international bodies, to have to do the work two or three times over, because different conversion factors are used, and different assumptions are made, for no very good reason. As to whether this work is better done by existing bodies or creating new ones, I think that one has to use existing expertise to the extent that it is reasonably good; it is often easier to improve something that exists than start completely *de novo*.

In long-run forecasting it is important to avoid conveying the impression that the result will be precise. I think, however, that subject to these qualifications, scientific forecasting is worthwhile, if only because the inevitable alternative is guessing on the spot—which is likely to be worse.

T. D. Ross (Shell International Petroleum Co. Ltd): The thought has occurred to me from time to time recently that part of the present problems, both in our industry and the coal industry in Europe, might be related to the increasing success in persuading people of the benefits of scientific forecasts. I remember, when I first came into this, that the standard line was that one should sway people away from hunch, hunch usually being the feeling that things cannot go on indefinitely as they have been doing. Over the period of the post-war years, I think, scientific forecasting has reached the point of persuading industry to assume things would go

on much as they have been in the past, and not to believe that things cannot go on at this optimistic rate. The result of this seems to be that, because within our global totals for the growth of energy that energy is supplied by a number of competing sources, and one has an optimistic view of one's ability to meet a calculated increment in the demand, there is a tendency, I believe, towards over-investment in energy supply. I remember the interest with which I read possibly one of the first published exercises, "Plans for Coal," which made some assumptions about the requirements for energy in the U.K. I think they were very limited assumptions, but it was, in fact, a very important document, for it was the basis of the tremendous amount of investment undertaken by the coal industry subsequently. I wonder if Mr Chantler would feel there was any reason for hesitation in regarding these global figures as a sound basis for calculating the return one could expect from capital investment decisions undertaken in the light of them.

Philip Chantler: Is the suggestion that scientific methods tend to inflate demand forecasts, and therefore investment, when hunch would tend to be more cautious?

T. D. Ross: It is really that if one sets a hard and fast global target, scientifically forecast at a higher level than hunch would suggest, because people tend to take a relatively pessimistic view of the future of the total market, one is likely to obtain an excess of supplies from the industries competing to meet that total. This is because, I think, that the separate industries, or perhaps companies within single industries, tend, on the other hand, to take an optimistic view of their chances to provide a share of the forecast increments in demand. In other words, had we taken earlier on, perhaps, the hunch of the coal industry, in particular, that things were going to be more competitive with more abundant energy supplies—and had not insisted on keeping to this very high rate of growth apparently scientifically determined—a lot of capital now invested in energy would have gone to other more productive uses. Much capital now invested is not productive at all because there is over-capacity at the moment in the energy-supplying industries.

Philip Chantler: This question seems to take one right into the field of psychology. Why should scientific forecasting lead to a higher estimate of total demand than hunches would give? Is it that scientific forecasters, who are ordinary human beings, tend to be regarded as demi-gods, so that their forecasts of the total demand for energy in, say, 1975 are accepted uncritically, and individual suppliers of fuel become less cautious in their investment plans than if they were guided only by their own hunches about future demand? I wonder, however, whether this is not an argument from the particular to the general. The scientific forecast might, in different conditions, be lower than people's hunches, and lead to less investment than would otherwise take place.

Dr E. F. Schumacher (National Coal Board): Since the coal industry has been mentioned, and speaking from the coal industry, I would like to say that the targets of the "Plans for Coal," or the higher target imposed on the coal industry by the Ridley Committee, have never affected investment decisions at all; and if one looks up the actual investment figures, they are now higher than they were in the period of unsatisfied demand. The whole point is that the period of gestation in the coal industry is a very long one, and the decisions on investment that is taking place now are not relevant to the present situation, but to a situation starting from 1970 and extending to the year 2070. So there need be no fear; these earlier targets have done no harm. But the problems raised by Mr Chantler are really of intense interest. I do not know if I am right in saying that everybody who has had to do forecasting professionally probably found himself like a pendulum, swinging one moment to the view that the less done the better, and the next moment to the opposite view. Because the situation seems to be that we have to do it, and we must be extremely careful not to believe in it. That means we have to keep two ideas in our heads at the same time, which is extremely difficult for the human race. But that is the situation. If we do not do it, it is silly not to use existing knowledge. I personally do not like the word "forecast," and prefer to speak of exploratory calculations. But I think part of this work has done a lot of good, speaking for the coal industry, although the Robinson Report, in the text, could not be more bear-ish for the industry. There they were following the prevailing mood, yet in the figures they found they just could not make things add up unless they gave the coal industry a trade, in 1975, of much the same size as it is now. That is very interesting. If these explorers had not explored, perhaps the current opinion, that coal is a dying industry and should be given a decent burial as soon as possible, would be doing even more damage than it is doing.

Could I perhaps raise one small critical point, and that is that I thought Mr Chantler was a bit unfair on Sir Harold Hartley by saying that Sir Harold tried to solve the problem of energy supplies solely by increasing coal output. In fact, in his prognostications, coal output would rise by 43 million tons, whereas the total demand would rise by 483 million. These figures I obtained from Mr Chantler's Table VI. So it was less than 10 per cent of the increase that was to be covered by coal, and thus the change from Hartley to Robinson is not as dramatic as all that. Robinson assumes a small decline, and Hartley just a small increase.

The philosophical questions raised in the paper are, I think, very interesting. This question of rough and ready forecasting or refined, does, I feel, have to be very seriously considered and I personally have come to the conclusion that it is necessary to use all available methods. But it is a mistake for Mr Chantler to give evidence in his paper that he has used them all. In fact, his paper should have given a few very bare statements so that nobody can believe that a lot of work has gone into it, because otherwise they will put much too much trust in it. Always we have to do it, but we must not believe in it, and we must not get other people (who do not know how impossibly difficult it is) to believe in it.

Secondly, I am much concerned over another question, and that is the meaning of these so-called forecasts. That rather bothers me. The Robinson Report, for instance, seems to state in many cases merely what is likely to happen, but then it changes very slightly and seems to suggest that here is a recommendation as to what ought to happen. I think that all those concerned with this kind of game should do a lot of hard thinking on this point; it must be made quite clear whether we are giving a forecast of what seems likely to happen if various tendencies that we know of continue, or whether we are saying that something ought to happen. I think that the documents that we have had from international agencies do not make a sufficiently clear distinction. I expect that one day committees or commissions like the Robinson Commission would critically discuss whether what is likely to happen is the right thing. That I

personally missed very much in the Robinson Report, but I shall not labour the point here.

Philip Chantler: I must question Dr Schumacher's suggestion that the Robinson Commission had to assume much the same coal production in 1975 as now in order to balance the energy budget. The figure was rather based on what the coal producers themselves told the Commission they expected to supply in that year, and what the Commission themselves thought could be sold in competition with other fuels. I agree that the Hartley Commission forecast only a relatively small increase in coal production, but they also forecast large increases in energy imports, and went on to urge the case for increasing indigenous production in order to reduce these prospective imports. The Robinson Commission were much more neutral than the Hartley Commission on this question: they were not greatly worried about the prospect of a large increase of energy imports. This is one of the main differences between the two reports.

H. Du Moulin (Shell International Petroleum Co. Ltd): I wonder if I could ask the speaker's opinion about two different types of forecast. I am thinking here, on the one hand, about the man who makes a forecast and gives a certain range, and says that by 1975 we can expect such and such a figure, within a range, say, of 10 per cent up or 10 per cent down, which fully admits how uncertain forecasting is; and, on the other hand, does not tell one very much. Then there is the man who may think of the saying, " Observe the turtle. It only makes progress when its neck is out," and he gives an exact figure for 1975. In the light of what Mr Chantler has been saying before, I would gather that he prefers the first approach, namely, that one is honest about it and admits there is a possibility of a definite deviation of the result. But the size of the deviation by itself is conjecture, so I would like the author's opinion on which of these two approaches he would definitely advise.

Philip Chantler: I would say definitely that in this sort of forecasting the less impression one gives of precision, the more realistic. In my view a range is preferable to a single figure with an estimated error of, say, minus or plus 10 per cent, because people forget the plus or minus 10 per cent, and only remember the central figure, which gives a spurious precision.

Miss M. M. Eccleshall (Shell International Petroleum Co. Ltd): Could I ask Mr Chantler if there is any maximum period beyond which he really feels it is pointless to attempt to forecast at all? It does seem to me that after about five years it is not very helpful for planning purposes to do a forecasting exercise, and if the period is as long as 15 years, while it may be very interesting to hear, for example, of the possible developments in energy supply and demand in Western Europe by 1975, it is not very practical, and is it of any real use at all? Would he indicate the maximum length of time beyond which, frankly, one might as well give up forecasting altogether?

Philip Chantler: I am much in sympathy with the questioner, but find it difficult to judge for how many years ahead forecasting can give significant results. One can only advise against forecasting further ahead than is necessary for decisions which have to be taken now. The further ahead the forecasts, the less valid they are, and the margin of error increases exponentially. Forecasts for A.D. 2050 are useless. In any case there may be nobody here by then.

The President then called for a vote of thanks to Mr Chantler, which was accorded with acclamation.

PROPERTY REQUIREMENTS FOR LIQUID ROCKET PROPELLANTS *

By E. M. GOODGER † (Fellow)

SUMMARY

An analysis is made of the properties necessary for liquid rocket propellants to give effective performance with acceptable handling. Typical propellants are examined against this requirement background, and their relative suitability assessed.

1. INTRODUCTION

In the literature there is a tendency to deal individually with rocket propellants, and to list their properties in the manner of a catalogue. This presentation is necessary eventually, when final details have to be settled after a choice of propellants has been made, but selection may be simplified by the comparison of individual properties over a range of propellant types. Furthermore, it is convenient to sub-divide these properties into those which determine the performance of the rocket engine and those which influence handling. In this paper the following definitions are implied:

Performance Characteristics. Factors with a major influence upon the project design and propulsive effectiveness of the rocket engine.

Handling Characteristics. Factors with a major influence upon the mechanical detail design of the rocket engine, the fuel system, the vehicle and ground-handling equipment, and on the economics of supply.

In general terms, performance is the attraction in the search for improved propellants, whereas handling imposes the problems. In many cases it is convenient to take liquid oxygen and a conventional hydrocarbon fuel of the kerosine type for reference purposes, so that the extent of improvements may be assessed quantitatively.

This paper has been prepared with the following objectives:

(i) To compare the performance characteristics of typical liquid rocket propellants.

(ii) To compare the handling characteristics of these propellants.

(iii) To assess the overall suitability by examining the propellants individually.

2. PERFORMANCE CHARACTERISTICS

2.1. *Reaction Energy*

Since most propulsive systems are based upon a chemical reaction, a high reaction energy per unit mass of reactant is the first essential. Generally, the process is one of oxidation, although alternative reactions, such as fluorination, are both possible and desirable.

The gravimetric heat quantities released by the oxidation of a number of elements are charted in Fig 1, and hydrogen is seen to have far and away the highest heating value, at 28,700 CHU/lb. Other promising elements, in descending order of oxidation energy, are beryllium, boron, lithium, carbon, aluminium, silicon, and magnesium. Since difficulties may be encountered with the use of hydrogen alone, these alternative elements must also be considered, for use either as additives or as hydrogen carriers.

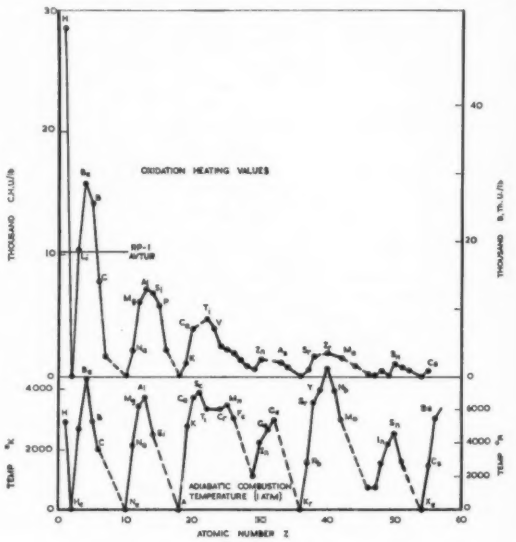

FIG 1

ELEMENTAL HEATING VALUES AND COMBUSTION TEMPERATURES [1]

In chemistry, the reaction energy is defined as the heat *added* to the products in order to regain the standard state after a reaction with the reactants originally at the standard state. An *exothermic* reaction, therefore, is indicated by a *negative* sign. The reaction energy requirement may thus be written

* MS received 24 November 1959.

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as max neg ΔH_r°, where the superscript $^\circ$ represents the standard state of 25° C and 1 atmosphere. Reaction energy may be expressed in terms of the heats of formation of the reactants and of the resulting products:

$$\Delta H_r^\circ = \Sigma\Delta H_f^\circ \text{ products} - \Sigma\Delta H_f^\circ \text{ reactants}$$

It follows that max neg ΔH_r° calls for products of max neg ΔH_f° and reactants of max pos ΔH_f°.

The heat of formation is derived from the following processes:

Elemental molecules (at standard state) —Atomization heat (Endothermic positive)→ Gaseous atoms —Bond energy (Exothermic negative)→ Compound molecules (at standard state)

Thus, $\Delta H_f^\circ = \Sigma\Delta H_a^\circ - \Sigma D(X - Y)$

where ΔH_a° represents atomization (or sublimation) heat required to convert the elemental molecules into gaseous atoms, and $D(X - Y)$ represents the bond energy required to dissociate an $X - Y$ bond into gaseous atoms.

As shown in Fig 2, the requirement of max neg ΔH_r° now develops into the four requirements of min and max pos $\Sigma\Delta H_a^\circ$ for the products and reactants respectively, and max and min pos $\Sigma D(X - Y)$ for products and reactants respectively. With individual hydrocarbons, values of these quantities included in Fig 2 and plotted in Fig 3 begin to show the fundamental requirements of molecular structure for high reaction energy. These may be summarized as low molecular weight with numerous multi carbon–carbon bonds, yet a high hydrogen content producing large concentrations of H_2O.

With hydrocarbon fuels produced commercially

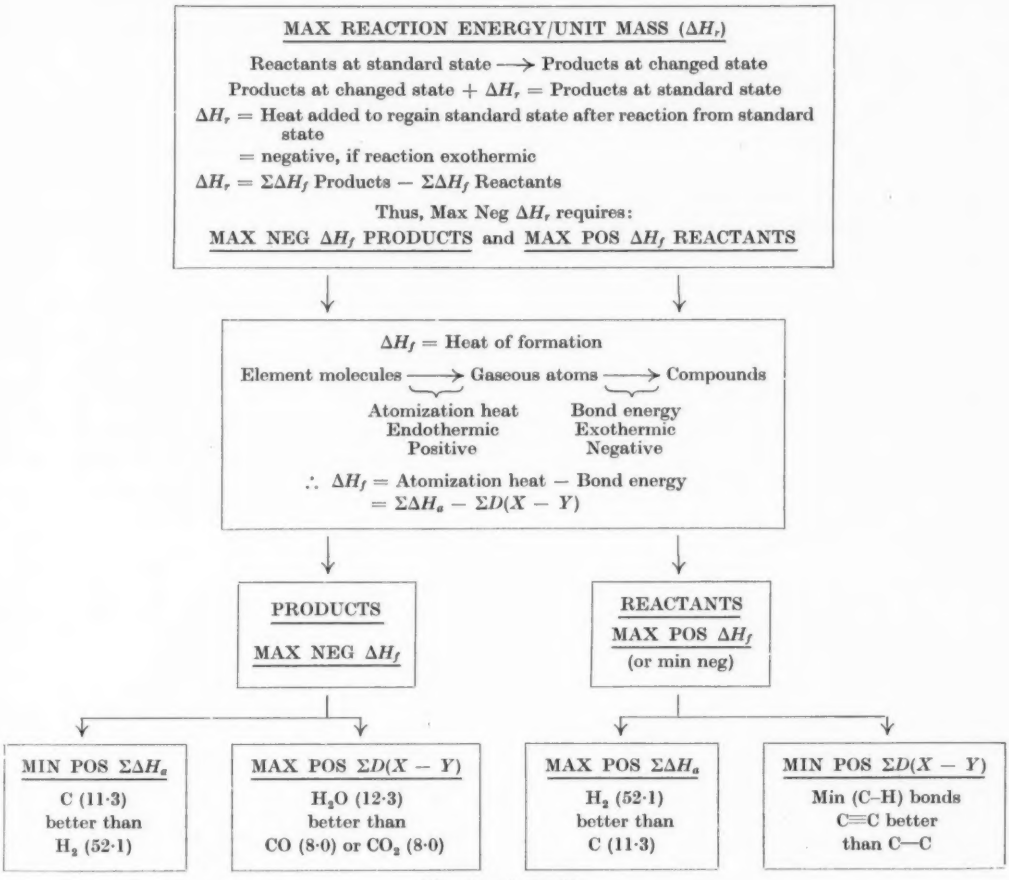
MAX REACTION ENERGY/UNIT MASS (ΔH_r)
Reactants at standard state → Products at changed state
Products at changed state + ΔH_r = Products at standard state
ΔH_r = Heat added to regain standard state after reaction from standard state
= negative, if reaction exothermic
$\Delta H_r = \Sigma\Delta H_f$ Products − $\Sigma\Delta H_f$ Reactants
Thus, Max Neg ΔH_r requires:
MAX NEG ΔH_f PRODUCTS and MAX POS ΔH_f REACTANTS
ΔH_f = Heat of formation
Element molecules → Gaseous atoms → Compounds
Atomization heat Endothermic Positive
Bond energy Exothermic Negative
$\therefore \Delta H_f$ = Atomization heat − Bond energy
$= \Sigma\Delta H_a - \Sigma D(X - Y)$
PRODUCTS
MAX NEG ΔH_f
REACTANTS
MAX POS ΔH_f
(or min neg)
MIN POS $\Sigma\Delta H_a$
C (11·3)
better than
H_2 (52·1)
MAX POS $\Sigma D(X - Y)$
H_2O (12·3)
better than
CO (8·0) or CO_2 (8·0)
MAX POS $\Sigma\Delta H_a$
H_2 (52·1)
better than
C (11·3)
MIN POS $\Sigma D(X - Y)$
Min (C–H) bonds
C≡C better
than C—C
All values in kcal/g.

FIG 2
REACTION ENERGY DIAGRAM

from petroleum feedstock, as shown in Fig 4, gravimetric heating value is found to fall by about 10 per cent for a 35 per cent rise in specific gravity from 0·7 to 0·95. The combined effects result in a rise in the volumetric heating value of about 25 per cent. An

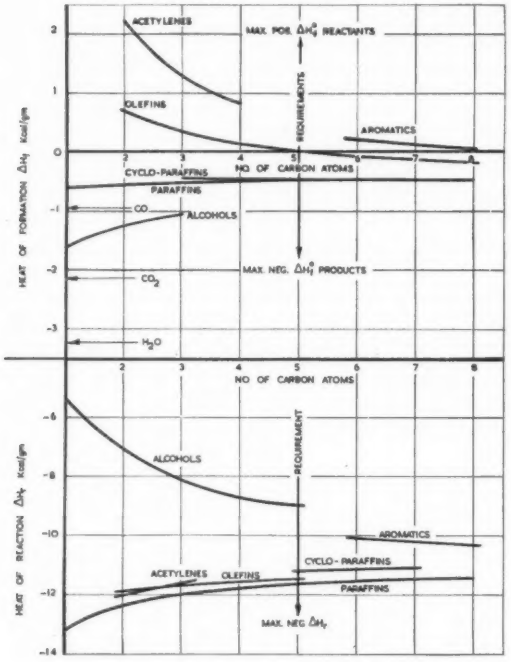

FIG 3

HEATS OF FORMATION AND REACTION OF HYDROCARBONS

Note: ΔH_f values derived from ref 2
ΔH_r values derived from ref 3

increased content of hydrogen, therefore, reduces the specific gravity and raises the gravimetric heating value until the ultimate is reached in hydrogen itself. The specific gravity of liquid hydrogen at its boiling point of −253° C is 0·071. In airborne considerations mass is a vital factor, so that the gravimetric energy requirement directs fuel selection towards low specific gravity fuels and liquid hydrogen. With high-speed vehicles operating within a gaseous atmosphere, however, aerodynamic drag imposes a minimum volume requirement. In these applications, therefore, a heavy fuel may be advantageous, and specific gravity can be increased appreciably by loading liquid fuel with finely-pulverized solid to form a slurry. This arrangement offers a practicable compromise between the attractive high density and the difficult pumpability of the solid alone.

The importance of replacing carbon as a hydrogen carrier is emphasized by the realization that, in aviation kerosine, carbon contributes about 86 per cent of the mass of the fuel, yet only 62 per cent of the energy. Hydrides are formed by boron, lithium, silicon, and magnesium in addition to carbon. Hydrides of nitrogen are also worth attention, since their heats of reaction are suitable, and the nitrogen can be considered as a temperature-controlling diluent. Fuels of high-energy interest, therefore, resolve themselves into the following groups:

(i) The hydrocarbons.
(ii) Liquid hydrogen.
(iii) Slurries of beryllium, boron, lithium, carbon, aluminium, silicon, and magnesium in a suitable high-energy carrier fluid.
(iv) Hydrides of beryllium, boron, lithium, silicon, magnesium, and nitrogen.

The heating values plotted against specific gravity in Fig 5 indicate dramatically the improvements available with the non-hydrocarbon high-energy fuels. Arbitrary curves have been constructed to connect the gravimetric and volumetric heating values of hydrogen, boron, and their compounds. The trends with specific gravity are similar to those noted with

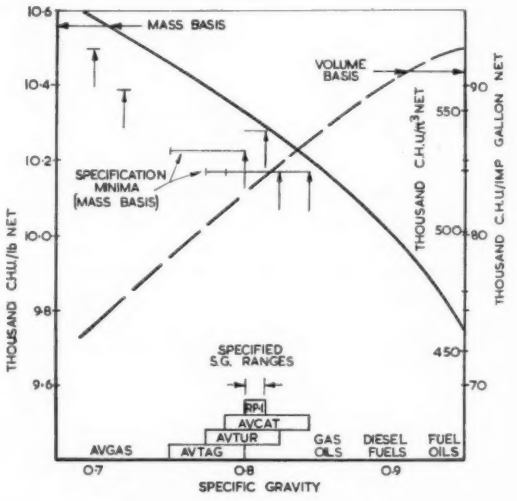

FIG 4

TYPICAL HEATING VALUES OF PETROLEUM FUELS

Code	*Fuel*	*D.Eng.R.D. No.*
AVGAS	Aviation gasoline	2485
AVTAG	Aviation wide-cut gasoline	2486
AVTUR	Aviation kerosine	2482
AVCAT	Aviation high flash kerosine	2488
RP-1	Rocket kerosine	

petroleum fuels. A 60/40 mass ratio boron-kerosine slurry is included, together with ammonia, hydrazine, and a typical alcohol.

Since both gravimetric and volumetric heating values are significant for high-speed applications within a gaseous atmosphere, the product of these two heating values can be compared with that for aviation

kerosine, and expressed as the " Performance Index," *i.e.*

$$\text{Performance Index} = \frac{\text{CHU/lb} \times \text{CHU/gal}}{K}$$

where K for aviation kerosine (AVTUR) is 840×10^6 approximately in consistent units. Fig 6 shows values

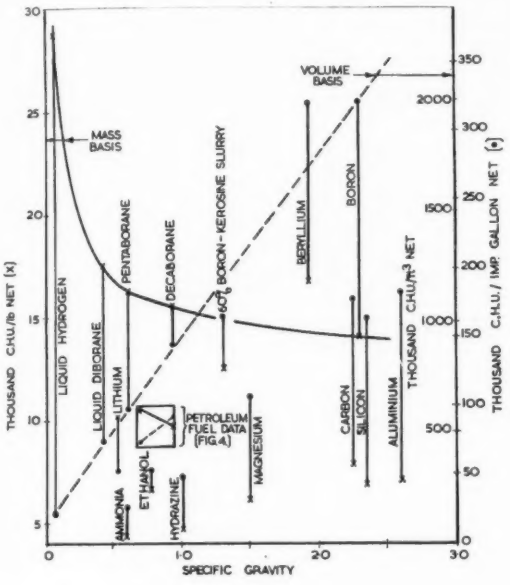

FIG 5

HEATING VALUES OF PETROLEUM AND NON-HYDROCARBON FUELS

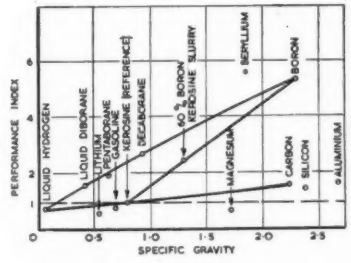

FIG 6

VALUES OF PERFORMANCE INDEX

of performance index plotted against specific gravity. Arbitrary curves have been constructed to connect the hydrogen–carbon and hydrogen–boron compounds. A more representative fuel for reference purposes might be RP-1, which is a pure, light-cut kerosine of low aromatic content, prepared especially for rocket applications. However, its properties are not far removed from AVTUR, and its performance index is approximately 1·02.

2.2. *Specific Impulse*

Combustion in the absence of diluent gases results in temperatures of 3000° C or more, compared with 2000° C met in most air-breathing engines. The thermodynamic behaviour of the product gases in their passage through the propelling nozzle (Fig 7) now becomes significant, and the performance of the propellants cannot be assessed upon the reaction energy alone. An overall assessment becomes possible by applying the Bernouilli expression to the gas flow through the nozzle, and calculating the exit velocity

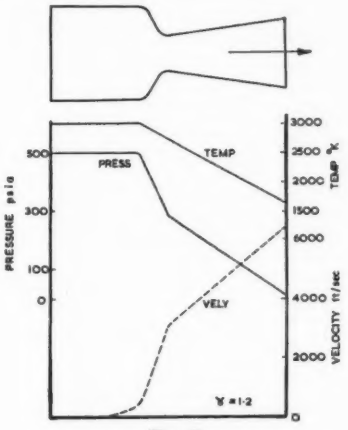

FIG 7

TYPICAL VARIATIONS WITH TEMPERATURE, PRESSURE, AND VELOCITY IN A ROCKET NOZZLE

V_e. This leads to an expression for the specific impulse, I_{sp}, which is the thrust produced with unit mass consumption rate of propellants (see Appendix).

$$I_{sp} = \frac{1}{32{\cdot}174}\sqrt{\frac{2\gamma}{\gamma-1}\frac{GT_c}{M}\left[1-(p_e/p_c)^{\frac{\gamma-1}{\gamma}}\right]}$$

where p_e = nozzle exit pressure (= atmospheric pressure under optimum conditions);
p_c = combustion chamber pressure;
γ = ratio of specific heats for propelling gases;
T_c = temperature of combustion chamber gases;
M = mean molecular weight of propelling gases.

The requirements for high specific impulse may now be written as follows:

(i) Min p_e/p_c (see Fig 8). For a given p_e, this represents a max p_c, which is a function mainly of nozzle throat area and of propellant consumption rate.

(ii) Min γ (see Fig 9). The value of γ is minimized by increasing the concentration of monatomic molecules in the propelling gases, and is thus a propellant function.

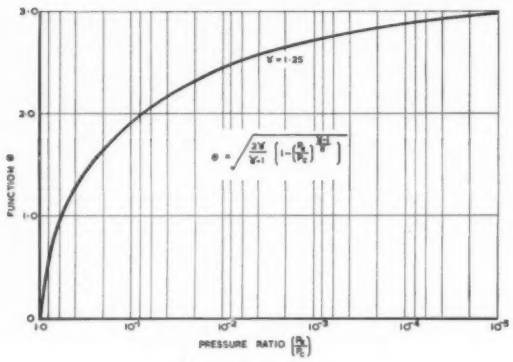

FIG 8

INFLUENCE OF PRESSURE RATIO UPON FUNCTION

See also ref 4

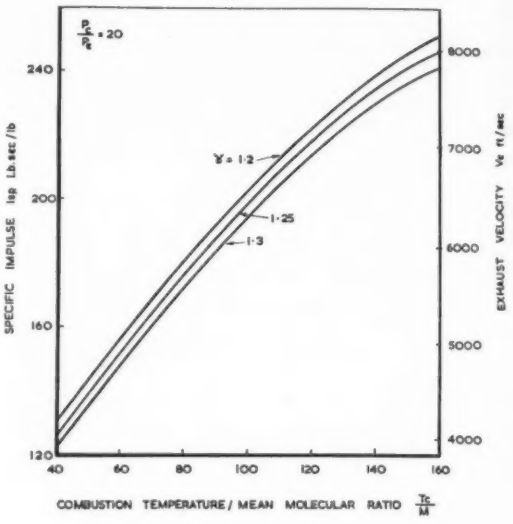

FIG 9

INFLUENCE OF $\frac{Tc}{M}$ RATIO AND γ UPON *Isp* AND *Ve*

Ref. 5. By permission

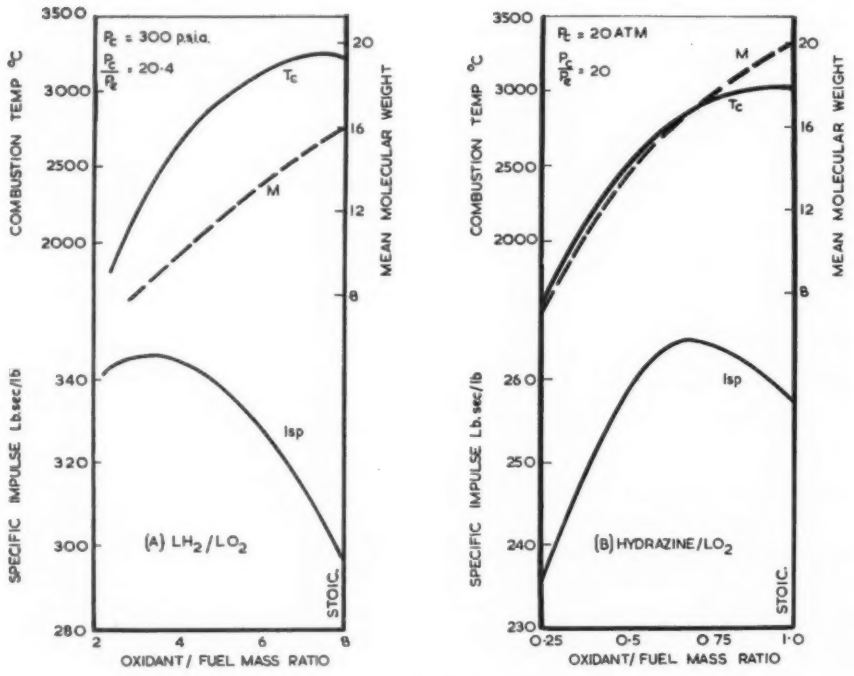

FIG 10

MIXTURE-RATIO PERFORMANCE CURVES

Ref 5. By permission

(iii) Max T_c (see Fig 9). Generally, the level of combustion temperature follows that of the heating value, as shown in Fig 1. Some discrepancies occur, however (*e.g.* *Ti*) due to the relative values of specific heat of the resulting products. Calculations for hydrocarbons in piston engines[13] show a striking example of this; an increased heating value resulting in a reduced T_c due to the influence of the greater quantity of water vapour produced. Hence T_c is a propellant function.

(iv) Min M (see Fig 9). This requires large concentrations of light products (*e.g.* water vapour), and is therefore a propellant function.

Mixture ratio is an additional variable which produces a change in a derived parameter from a combination of changes in individual parameters. Figs 10 (*a*) and (*b*) show mixture ratio curves for two typical propellant pairs. Generally, although the maximum non-dissociated temperature occurs at the stoichiometric ratio, the influence of dissociation, together with the relative values of product heat capacities, is such that the maximum dissociated temperature lies on the fuel-rich side of stoichiometric. With fuels of high hydrogen content, therefore, producing large concentrations of water vapour, the reducing value of M with fuel enrichment brings the specific impulse peak further over on the fuel-rich side. With these fuels, also, the low specific gravity compared with most oxidants tends to move the peak of the volume impulse curve back towards stoichiometric.

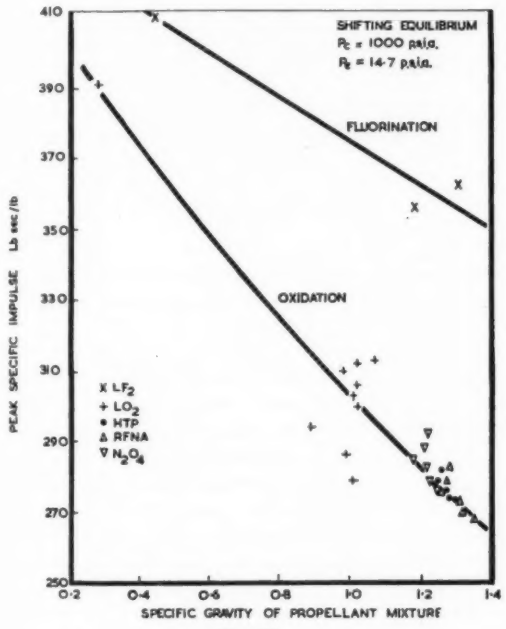

FIG 11

RELATIONSHIP BETWEEN PEAK SPECIFIC IMPULSE AND SPECIFIC GRAVITY

Derived from ref 6

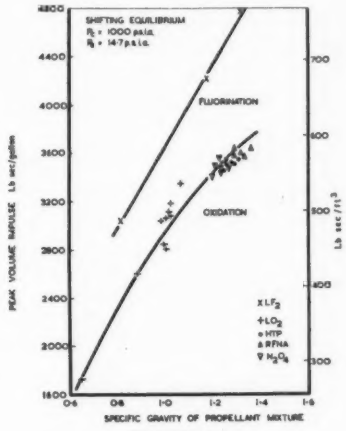

FIG 12 (*a*)

RELATIONSHIP BETWEEN PEAK VOLUME IMPULSE AND SPECIFIC GRAVITY (SMALL-SCALE PLOT)

Derived from ref 6

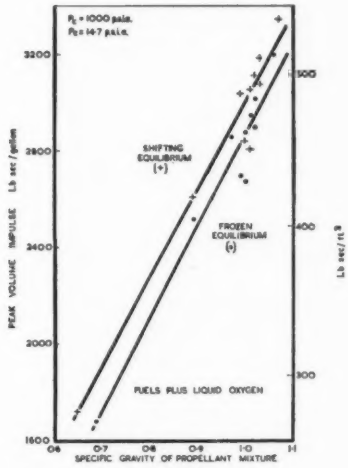

FIG 12 (*b*)

RELATIONSHIP BETWEEN PEAK VOLUME IMPULSE AND SPECIFIC GRAVITY (LARGE-SCALE PLOT)

Derived from ref 6

From the data presently available, a general direct relationship is found to exist between peak specific impulse and CHU/lb propellant mixture. This relationship is reflected in the fall in peak specific impulse with increased specific gravity, shown in Fig 11. Because of the inclusion of specific gravity in the impulse term, a plot of volume impulse shows a closer direct relationship with specific gravity, as in Fig 12 (*a*). The large-scale re-plot in Fig 12 (*b*) indicates

a difference of about 8 per cent between shifting and frozen equilibrium values of peak volume impulse.

Since it is difficult to predict the specific impulse from a single characteristic property of a fuel, comparisons have been made in the form of charts (Figs 13 and 14) with the fuels arranged in descending order of peak specific impulse and peak volume impulse respectively. Arbitrary curves have been drawn to connect these values for four different oxidants and for fluorine. The charts therefore also indicate the effectiveness of oxidants, and show that maximum specific impulse is produced with hydrogen and fluorine as a propellant pair, and maximum volume impulse with hydrazine and fluorine.

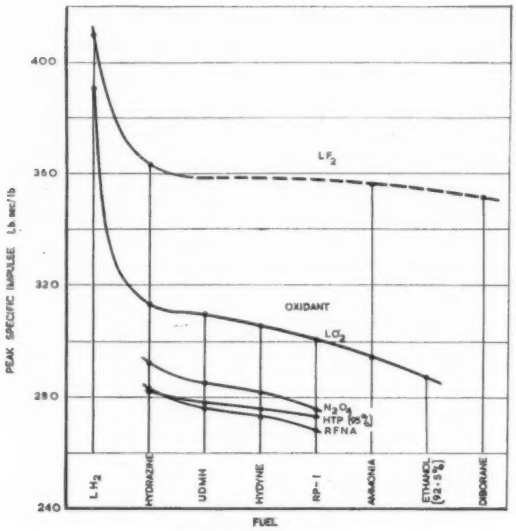

FIG 13

COMPARISON OF PEAK SPECIFIC IMPULSE VALUES FOR BI-PROPELLANTS

Derived from ref 6

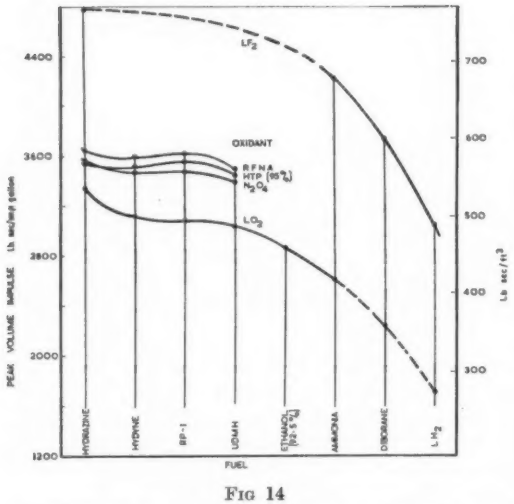

FIG 14

COMPARISON OF PEAK VOLUME IMPULSE VALUES FOR BI-PROPELLANTS

Derived from ref 6

2.3. *Combustion Characteristics*

Since liquid propellants are invariably sprayed into the combustion chamber, properties which provide for fine atomization and rapid vaporization are necessary for a compact flame and a short chamber length. These properties may be listed as follows:

(i) *Spray formation*

Specific gravity—Slight, direct effect on droplet penetration.

Viscosity—Direct effect on both droplet diameter and penetration.

Surface tension—Direct effect on droplet diameter and penetration.

(ii) *Spray vaporization*

Volatility—Direct effect on vaporization rate

Thermal conductivity—Direct effect on vaporization rate.

Specific heat—Inverse effect on vaporization rate.

The required fuel properties, therefore, are a low viscosity, surface tension, and specific heat, and a high volatility and thermal conductivity.

Once flame has been initiated, and the supply of propellant vapour assured, the length of the combustion chamber can be minimized by means of a high flame speed. Flame speeds of the hydrocarbons lie at a very low level, ranging from about 2–4 ft/sec when burning in air at atmospheric pressure, about ten times this when burned in oxygen, and increased further when burning under high pressure. The flame speeds of hydrogen, and the boron hydrides, are considerably greater than those of the hydrocarbons.

The mixture range of inflammability is normally associated with flame speed. A wide inflammable range is a valuable property where changes in propellant flow rate are likely to be encountered, since flame stability is improved and flame-out avoided. The inflammable range of hydrogen is very much wider than that of the hydrocarbons.

For extended operation, clean combustion is essential, with the absence of nozzle fouling by deposit build-up. With most fuels, this is achieved by control of mixture ratio to avoid over-enrichment of fuel. When condensation and freezing points of combustion products are high, the danger exists of liquid and solid particles forming in the propelling gas stream and depositing on the internal surfaces of the nozzle. Deposit tendencies exist with hydrocarbons of high carbon content, with boron fuel, and with slurries.

Aluminium, with an oxide freezing temperature of about 2000° C, is particularly difficult in this respect, and Fig 15 shows the extent of deposit accumulated

FIG 15

COMBUSTION CHAMBER DEPOSITS WITH ALUMINIUM SLURRY FUEL

in a 2-inch bore duct during a 30-second test burning a 30 per cent aluminium–kerosine slurry in air at a low fuel/air ratio.[7]

3. HANDLING CHARACTERISTICS

3.1. *Volume Impulse*

Probably the foremost requirement for rocket operation within a gaseous atmosphere is a maximum volume impulse in order to minimize fuel system bulk and aerodynamic drag. Since this property is so closely dependent upon specific impulse, its discussion has been included in the performance section. The associated controlling property, specific gravity of the propellant mixture, is seen to have a general direct relationship with volume impulse (Fig 12) so that a high specific gravity is generally desirable for atmospheric operation.

3.2. *Vapour Pressure*

High-speed operation within a gaseous atmosphere leads to high bulk fuel temperatures due to kinetic heating. Thermal insulation or refrigeration may be necessary. Vapour pressure rises with temperature at an increasing rate (Fig 16), and must be either resisted by the strength of the tank structure or relieved by tank venting. The former incurs weight penalties, whereas the latter gives rise to vapour loss, particularly at high altitude. A low vapour pressure is required, there, and ref 8 suggests a maximum limit of 20 psia at 230° C.

3.3. *Thermal Stability*

Prolonged exposure of hydrocarbon fuels to kinetic heating leads to the formation of a sediment of insoluble oxidation products which tend to filter blockage. Maximum thermal stability is essential for atmospheric operation due to kinetic heating, and for spatial operation due to radiation heating. The thermal stability of hydrocarbon fuels is currently assessed in a heated filter rig, and a thermally-stable kerosine (JP 6) is specified for jet aircraft.

3.4. *Viscosity–Temperature Relationship*

A minimum viscosity–temperature dependence and low freezing point are desirable in order to retain pumpability at low temperatures (*e.g.* starting conditions in Arctic regions, or in a high-altitude aircraft operating at a relatively low speed) yet to provide at high temperature a viscosity level sufficient to lubricate metering valves in the control system. This viscosity requirement conflicts with that for satisfactory spray formation, which illustrates the need

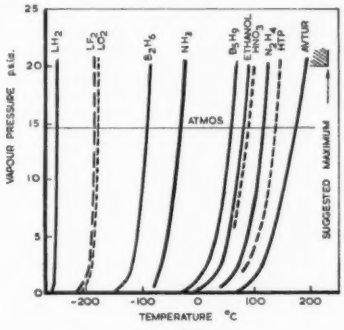

FIG 16

TEMPERATURE VARIATION OF PROPELLANT VAPOUR PRESSURE

for compromise in property selection. The fall in viscosity with temperature rise for some rocket propellants is shown in Fig 17.

3.5. *Heat Capacity*

A high specific heat, together with a high latent heat of vaporization, permits smaller heat transfer surfaces and lower flow rates of coolant. Some values of specific and latent heats are included in Table I.

3.6. *Combustion Characteristics*

Fuels burning with high luminosity, caused by glowing particles in the flame, are liable to form smoke, and to promote metal fatigue due to radiant heat transfer to the combustor walls. The aromatics fall into this category. One valuable property which helps to ensure ignition, flame stability, and re-light at altitude is the spontaneous ignitability of the propellants on contact in the liquid phase. This phenomenon is termed " hypergolic " ignition, and is exhibited by hydrazine and HTP, aniline and nitric acid,

TABLE I

Representative Properties of Liquid Propellants

Property \ Material	Hydrocarbons				LH_2	60/40 Boron AVTUR slurry	Hydrides					Oxidants			
	AVTUR	RP-1	Polycyclic naphthenes	Ethanol			B_2H_6	B_5H_9	NH_3	N_2H_4	UDMH	LF_2	LO_2	HTP	HNO_3
Lower heating value CHU/lb	10,250	10,280	10,270	6,650	28,700	12,500	17,400	16,200	5,720	4,720	7,870				
Lower heating value CHU/gal	82,000	83,000	88,900	52,700	20,090	164,000	74,800	98,800	35,000	47,700	61,400				
Performance index	1·00	1·02	1·09	0·42	0·69	2·44	1·55	1·90	0·24	0·27	0·58				
Sp gr at 60/60° F	0·8	0·8	0·866	0·792	0·071 b.p.	1·31	0·43 b.p.	0·61	0·61	1·01	0·78	1·51	1·14 b.p.	1·35	1·56
Spec heat at 60° F CHU/lb° C	0·50			0·61	2·33 b.p.		0·48	0·57	1·12	0·75	0·65	0·37	0·4 b.p.	0·61	0·42
Vaporization heat CHU/lb	67			204	109		125	122	326		134	41	51	346	115
Boiling point ° C	150/300	185/274	201/275	80	−253	150+	−93	63	−33	114	63	−188	−183	152	86
Freezing point ° C	−40	−40	−60	−118	−259	−40	−165	−47	−78	2	−58	−220	−220	−22	−42
Flash point ° C	37·8	43·3		21						52	1				
Spontaneous Ign temp °C, in air at 1 atm	254			439	570				651		250				
			Typical												

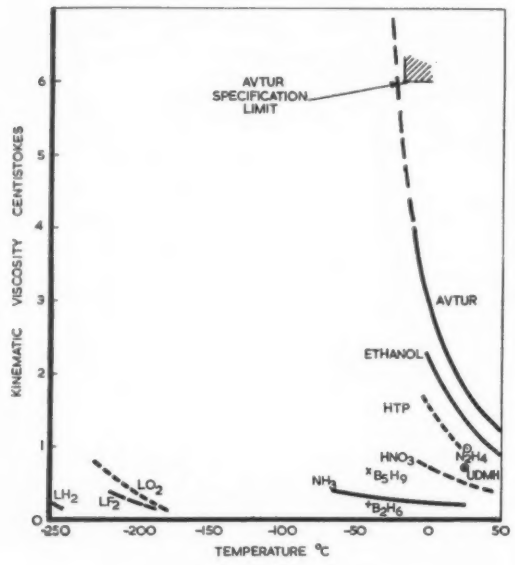

FIG 17

TEMPERATURE VARIATION OF PROPELLANT VISCOSITY

and some other propellant pairs. It simplifies the detail design of the rocket engine by the elimination of electrical ignition equipment, but inevitably increases the risk of fire in handling. A valuable development is the system of "thermal" ignition, in which HTP is decomposed catalytically in the combustion chamber, the decomposition temperature being sufficient to ignite kerosine spontaneously. This preserves the convenience of spontaneous ignition within the chamber, without the increased fire danger outside it.

3.7. *Uniformity, Availability, Cost*

Greater constancy of purity and quality permits smaller tolerances in design, and hence saves weight. Specification limits ensure uniformity of product quality, but limits can be set only as uniformity of supplies, control of processes, and reproducibility of test techniques permit. Cost of the finished product depends upon availability of supplies and complexity of processing. Beryllium, for example, is in such small supply that its consumption as a rocket propellant is impracticable. Boron, on the other hand, exists in nature mainly in the oxide form as a borate. Since this is also the resultant combustion product, reaction energy must be supplied during processing in order to produce elemental boron, and this adds to the cost.

3.8. *Storage, Transfer, Transport*

For ease of handling, propellants should exist in the liquid phase at normal temperatures. Gases require

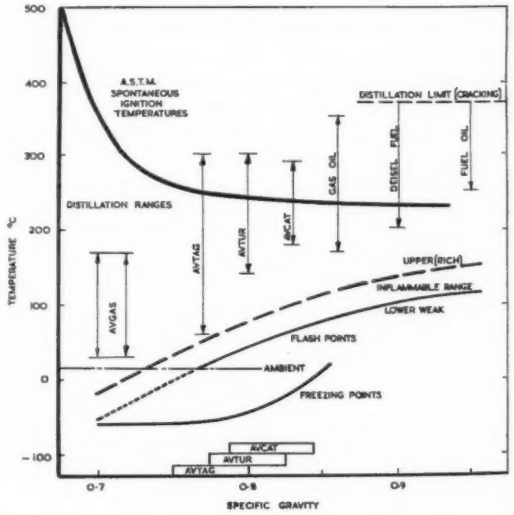

FIG 18

TYPICAL VALUES SHOWING TRENDS IN PETROLEUM FUEL PROPERTIES [8]

either pressurized containers, which are bulky and heavy, or cryogenic equipment, which tends to be expensive and fragile. Solids provide maximum density, but are difficult to pump. Propellants should be inert and stable, with no physiological hazards or corrosive tendencies. Stability at extremes of temperature is required, with maximum fire safety. These requirements dictate a boiling point well above ambient and a freezing point well below, compatibility with a wide range of structural materials, a high flash point, a high spontaneous-ignition temperature, and a high cracking (decomposition) temperature. Some of these properties are plotted for petroleum fuels in Fig 18. Acetylene, with a high heating value/lb, is rejected due to its detonability when pressurized.

4. OVERALL SUITABILITY

4.1. *Hydrocarbons*

Petroleum fuels offer the immediate attractions of high availability and relatively low cost, coupled with reasonable performance and an extensive backlog of handling experience.[8] Aviation kerosine and RP-1 represent the optimum types of rocket fuel within the commercial product range, but certain individual

TABLE II

Relative Suitability of Liquid Rocket Fuels
(Derived from ref 9)

Best = 1 Worst = 5

Property	Material	Hydrocarbons	LH_2	Slurries	Non-carbon hydrides	Hydrazine
Performance	Heat content	3	1	3	2	5
	I_{sp} with LO_2	4	1	5	3	2
	Combustion	3	1	5	4	2
Handling	Specific gravity	3	5	1	4	2
	Vapour pressure	1	5	2	2	4
	Thermal stability	2	1	3	4	4
	Viscosity–temperature	1	5	4	2	3
	Specific heat	2	1	2	4	4
	Uniformity	4	1	5	3	2
	Availability and cost	1	4	2	4	3
	Storage, transfer, transport	1	5	4	3	2
Overall rating	Air-breathing	2	1	4	3	4
	Rocket	2	1	5	4	3

hydrocarbons, although of reduced availability, offer overall improvements. Conclusions drawn from such an overall assessment[9] suggest that the polycyclic naphthenic type hydrocarbons provide the best compromise of high hydrogen content, high density, low vapour pressure, good thermal stability, and good low temperature characteristics. The materials examined include decalin, phenanthrene, fluoranthene, and *iso*propyl bi*cyclo*hexyl. The supply situation would be eased by specifying petroleum fuels rich in polycyclic naphthenes rather than the pure hydrocarbons alone.

4.2. *Liquid Hydrogen*

Hydrogen is seen to exhibit the ultimate in gravimetric heat content and, since it realizes a fairly high combustion temperature with products of low molecular weight, it also produces a maximum specific impulse. With its attractive combustion characteristics of high flame speed, wide mixture range of inflammability, and clean burning, hydrogen represents the optimum in performance.

On the handling side, the very low density of hydrogen renders the liquid phase essential for aircraft use, and the low density of liquid hydrogen completely eliminates the superiority in impulse when expressed on a volume basis. The low boiling point of liquid hydrogen incurs problems of vapour pressure and of material suitability. The vapour loss when stored in a double-walled vacuum container is of the order of 4 per cent per day. Shielding with a layer of liquid nitrogen (bp −196° C) can reduce this to 0·017 per cent per day. The latter type of vessel is comparatively fragile and will not withstand pressure differences in excess of about 20 psi. For storage in aircraft, attention is turning more towards the "polar vacuum" technique, where the vacuum chamber is filled with a powdered mixture of aluminium with silica, "Perlite," or other solid. This reduces the radiation heat loss, which is proportional to the fourth power of the temperature difference, but increases slightly the conduction heat loss. When paired with liquid oxygen, the oxidant might be used to replace liquid nitrogen for shielding purposes to give a compact, but highly inflammable installation.

Most ferrous alloys and many other metals undergo recrystallization and become embrittled between ambient temperature and −253° C, although their tensile strength may increase. Metals which are considered suitable for use with liquid hydrogen are copper, 18-8 stainless steel, Inconel, and Monel. Natural rubber is useless at these low temperatures, but PTFE retains resistance to shock. An interesting side effect is the solidification of oxygen if permitted to approach the surface of liquid hydrogen. The oxygen crystals sink in the liquid hydrogen to form a highly inflammable slurry. On pumping, it is found that the crystals collect a charge of static electricity, and that the sparks produced during fracture of the crystals are capable of initiating a violent explosion.

The low viscosity of liquid hydrogen permits high pumping efficiencies. Ball bearings have been operated successfully at high speeds, using liquid hydrogen as the lubricant. The high specific heat is attractive for coolant purposes, but the low boiling point means that the fuel rapidly vaporizes. Since hydrogen is the earth's ninth most abundant element, availability is no problem, and the production of gaseous hydrogen has developed on a wide scale. Liquefaction demands fairly extensive equipment due to the large heat extraction necessary. Hydrogen exists in both an *ortho* and a *para* form, and the natural *ortho–para* conversion in the liquid phase releases more than sufficient energy to boil off the converted *para* hydrogen. For long-term storage,

the *para* form is essential and can be achieved by catalysis.

4.3. *Slurries*

Inspection of Fig 19 shows that the introduction of solid materials into a hydrocarbon carrier fluid results

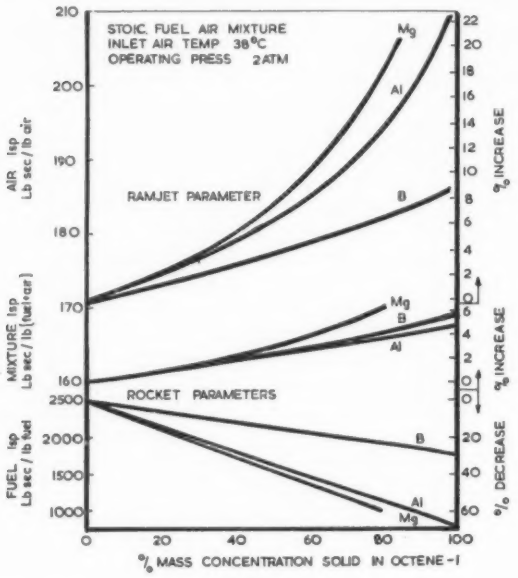

FIG 19

SPECIFIC IMPULSE VALVES FOR SLURRY FUELS

Derived from ref 10

in a progressive *reduction* in specific impulse expressed on a fuel mass basis, and a slight increase only in specific impulse expressed on a basis of mixture with air. When based on air alone, the concentration of solid is seen to be effective in increasing performance, so that slurry fuels appear to be attractive for ramjet applications. For rocket operation in a gaseous atmosphere, volume impulse is significant, and calculations made with the fuel–air results from Fig 19 show an increase of 12·75 per cent on volume impulse for the 80 per cent magnesium–octene slurry:

Propellant	Mixture volume Impulse, lb sec/gal of liquid propellant
Stoic octene-1 and air	1420
Stoic 80% boron/20% octene-1 and air .	1567
Stoic 80% aluminium/20% octene-1 and air	1552
Stoic 80% magnesium/20% octene-1 and air	1601

Similar improvements would be expected with oxygen as the oxidant.

Combustion tests reported in ref 11 showed that magnesium–hydrocarbon slurries burned readily and efficiently without deposition even under conditions where the liquid hydrocarbon alone would not burn. Successful flight tests were also conducted with a small ramjet. Boron slurries burned less readily than petroleum-based jet fuels and gave rise to objectionable deposits in the combustor. Aluminium slurries generally suffer from deposition troubles, unless porous-walled combustors are used.

On the handling side, the maximum mass concentration of solid is limited to about 50 or 60 per cent from considerations of pumpability and of settlement. Research at Cranfield into the preparation and physical behaviour of a 50 per cent mass slurry of powdered aluminium, of six micron average particle size, in aviation kerosine showed that suspension stability can be achieved by the incorporation of 0·5 per cent mass of aluminium octoate which, on heating, increases the viscosity of the kerosine by the formation of a gel.[12] Since the resulting slurry is difficult to pump or spray, a surface-active agent must also be added to act as a dispersant. One constituent of the surface-active agent dissolves in the kerosine, and the remainder attaches itself to the surface of the solid particles, so relieving the interfacial tension and promoting fluidity. Of the materials tested at Cranfield, polyoxyethylene sorbitol mono-oleate was found to be satisfactory when used in a mass concentration of 0·1 per cent in the above slurry.

Abrasion of pumps and systems would be a severe problem with slurries, particularly when using boron, which is second only to diamond in hardness.

4.4. *Hydrides*

Of the possible replacements for carbon in the hydrocarbons (*i.e.* carbon-hydrides), only beryllium, boron, and lithium offer a greater energy content. The heating value of beryllium hydride is some 60 per cent higher than that of aviation kerosine, but beryllium is not a practicable fuel in view of its extreme scarcity, toxicity, and the demands of the nuclear power industry. The heating value of lithium hydride is little better than that of aviation kerosine. The boron hydrides (*i.e.* boranes) of interest have been shown to be diborane (B_2H_6), pentaborane (B_5H_9), and decaborane ($B_{10}H_{14}$), which exist in the gaseous, liquid, and solid phases respectively at normal temperatures. Diborane condenses at −92° C, pentaborane freezes at −46·7° C and boils at 63° C, whereas decaborane melts at 99·4° C. Boron itself melts at about 2200° C.

Gaseous diborane ignites spontaneously in air and is readily explosive. Its violent reaction in the presence of moisture makes handling difficult, but offers possibilities of underwater propulsion. As with many boron compounds, diborane is toxic and has a disagreeable odour.

As a liquid fuel, pentaborane is more attractive from the handling viewpoint. It does not ignite spontaneously in air when cool, but may explode when hot. It is liable to decompose on standing, giving off hydrogen gas and forming heavier boranes which are solid but dissolve in the parent pentaborane. This

decomposition is slow, even in the presence of moisture, and results in boric acid. Pentaborane is also toxic. Decaborane is solid and has a lower performance, but it is less toxic and has a low vapour pressure. Most structural metals, except lead and copper, appear to be compatible with the boranes. Mild steel cannot be used for storage vessels, due to embrittlement following the release of hydrogen gas.

In view of these problems, a valuable expedient is the compounding of carbon with boranes to produce carboboranes. The carbon is added in the form of alkyl groups, such as the ethyl radical. Performance suffers slightly, but alkylation creates a stabilizing effect and reduces the toxicity of the combustion gases. In America the Olin-Mathieson Chemical Corpn produces carboboranes under the designation HEF, *i.e.* high energy fuels, whereas the Callery Chemical Co designation is HiCal.

In ramjet applications, fuels of a pyrophoric (spontaneously ignitible in air) nature are attractive, since their inflammable mixture range is much wider than that of hydrocarbon fuels and they burn at lower pressures. These properties permit the use of smaller, lighter, and more reliable ramjets, capable of economic high-speed operation at very high altitudes. They may also be used as turbojet ignition fluids and as anti-screech additives in rocket engines. The pyrophoric nature of some boron compounds, although giving rise to handling difficulties, is attractive performance-wise, and tests are proceeding with triethyl borane (TEB), as well as triethyl aluminium (TEA) and trimethyl aluminium (TMA).

Of the nitrogen hydrides, useful performance is exhibited by ammonia (NH_3), hydrazine (N_2H_4), unsymmetrical dimethyl hydrazine or UDMH ($N_2C_2H_8$), and "Hydyne," which is a 60/40 mass mixture of UDMH and diethylenetriamine (DET). In general, nitrogen hydrides are toxic, but their combustion products are inert. They are inflammable and form explosive mixtures with air. Ammonia has a high vapour pressure, but a high specific heat.

Hydrazine is spontaneously ignitible with nitric acid and with HTP. Hydrazine is generally used in the hydrate form, which is equivalent to a hydrazine concentration of 64 per cent.

4.5. *Oxidants*

Discussion of the properties of oxidants has received a thorough treatment in the literature, but, for completeness, a brief review is included. Fluorine is considered in this category, since its reaction with a fuel results in the evolution of energy. Fluorine is the most powerful "oxidizing" agent known, reacting with practically all organic and inorganic materials. It provides the highest specific impulse and, with its high specific gravity, the highest volume impulse. It has a very high vapour pressure and its low boiling point makes necessary the insulation of storage equipment. Reaction with many metals is slow at ambient temperature, resulting in a protective film of metallic fluoride. For this reason, such metals as iron, aluminium, magnesium, copper, and brass are compatible, if the temperature is controlled. Fluorine is very toxic.

Liquid oxygen also provides rapid reactions, high flame speeds, and high combustion temperatures. It, too, is a cryogenic material, with its attendant problems of vapour loss and low-temperature compatibility. Vacuum jacketing reduces vapour losses to about 0·1 per cent per day in bulk storage, but losses from current designs of aircraft tank are of the order of 7 per cent per hour. Thermal insulation reduces tankage costs, but the most effective insulants are also inflammable. The mixture ranges of inflammability of most fuels are widened considerably in combination with oxygen, compared with those in air, and the fire hazard is further increased, since the freezing of water from the surrounding atmosphere makes for easier generation of sparks. Since the spontaneous ignition temperature of most materials is lower in oxygen than in air, liquid oxygen cannot be used as a wall coolant. Availability of oxygen is no problem, and liquefaction can be carried out in mobile plants if necessary. Liquid ozone is more attractive from the performance and density points of view, giving an increase in specific impulse of about 10 per cent. Explosive decomposition is likely on contamination by dust or other small impurities, unless the mass concentration of ozone is reduced below 30 per cent by dilution with oxygen. The higher volatility of oxygen results in a progressive rise in ozone concentration during storage, and this risk is not eliminated by refrigeration, since ozone and oxygen then tend to separate out. Ozone is extremely toxic above a concentration of about 0·1 ppm.

High Test Peroxide provides a useful level of performance with most fuels and is stable in storage. If protected from temperature rise and the ingress of contaminants, the decomposition loss does not exceed about 1 per cent per annum in temperate zones and 3 per cent in the tropics. The decomposition temperature ranges from 450° to 996° C (80 to 100 per cent concentration) and the vapour is very active, so that flushing of the system is necessary after draining. A number of materials, including silver and the permanganates, catalyse decomposition and permit the use of HTP as a monopropellant or a source of auxiliary power. Pure aluminium and stainless steel are suitable structural materials for use with HTP.

High strength ("fuming") nitric acid, which is prefixed "red" when it contains up to 30 per cent of dissolved oxides of nitrogen, gives a performance comparable with HTP. It is slightly hygroscopic, and its corrosivity to aluminium increases with water content. It reacts with most organic materials, and may cause fires on contact with wood or other cellulose

products. Fuming nitric acid does not inflame, but will ignite spontaneously with some fuels. The low surface tension enables the liquid to creep over surfaces, and the fumes evolved are highly toxic. Aluminium, stainless steel, and high silicon irons are suitable structural materials, particularly when corrosion inhibitors are incorporated in the acid.

The nitrogen peroxides, in the form of the mixed oxides, also give comparable performance. A typical mixture of 70 per cent N_2O_4 and 30 per cent NO appears to meet the engineering requirements of high chemical stability, good corrosion resistance, low freezing point, and reasonably low vapour pressure. With dry peroxides, carbon steel and many other structural materials are suitable, but stainless steels are necessary under wet conditions.

5. CONCLUSIONS

(i) A high heat of reaction is a basic requirement for a rocket propellant pair, but this is modified by the thermodynamic behaviour of the combustion gases in the propelling nozzle. Consequently, any realistic indication of propellant performance must be based upon the resultant thrust.

(ii) A high combustion temperature is necessary for high thrust, but cooling problems are intensified, and certain propellants only are suitable as coolants.

(iii) A general increase in specific impulse is found with a decrease in specific gravity of the propellant mixture.

(iv) Liquid hydrogen offers the ultimate in specific impulse for chemical propellants, but handling difficulties are severe.

(v) Liquid fluorine is the most energetic reacting medium available for use with rocket fuels.

(vi) A general increase in volume impulse is found with an increase in specific gravity of the propellant mixture.

(vii) Hydrocarbon fuels still represent a practicable compromise for rocket applications.

(viii) Non-carbon hydrides appear to be the next most attractive fuels for rocket applications.

(ix) Slurry fuels are more suited to air-breathing propulsive units.

Some typical rocket applications of liquid bi-propellants are shown in Table III.

6. ACKNOWLEDGMENTS

Figs 9 and 10 included with permission from G. P. Sutton, "Rocket Propulsion Elements," 1956, John Wiley & Sons Inc.

TABLE III

Typical Liquid-Propellant Rockets

Vehicle	Engine	Sea-level thrust, lb	Fuel	Oxidant	Remarks
"Thor"	Rocketdyne, IR-79 sustainer	150,000	RP-1	LO_2	I.R.B.M. (RAF)
"Atlas"	Rocketdyne,	165,000	RP-1	LO_2	I.C.B.M. (U.S. Strat. Air Command)
	2-LR93 Boost	60,000	RP-1	LO_2	
	1-LR105 sustainer				
De-H. Prop., "Blue Streak"	Rolls-Royce, 2 engines	Assumed 150,000 each	Assumed hydrocarbon	Assumed LO_2	L.R.B.M.
Saunders-Roe "Black Knight"	Bristol-Siddeley Gamma Mk 201	16,400	Kerosine	H.T.P.	Upper atmosphere and re-entry
L.R.B.A. "Veronique"	L.R.B.A	8,800	Turpentine *	Nitric acid *	Upper atmosphere (I.G.Y.)
Aerojet-General "Aerobee"	Aerojet	4,000	Aniline *	Nitric acid *	Upper atmosphere
Martin "Viking"	Reaction Motors XLR 10	20,000	Ethanol	LO_2	Sounding
"Vanguard"					
Stage 1	GEC Aerojet	27,000	RP-1	LO_2	Satellite carrier
Stage 2		8,000 (alt)	U.D.M.H.	Nitric acid	
Stage 3		2,300 (alt)	Solid		
"Nova"					
Stage 1		4 × 1,500,000	RP-1	LO_2	N.A.S.A. advanced Space Laboratory Project
Stage 2		1,500,000	RP-1	LO_2	
Stage 3		80,000	LH_2	LO_2	
Stage 4		40,000	LH_2	LO_2	
Stage 5		6,000	Storable liquids		

* Hypergolic pairs

Turpentine (Pinene)	$C_{10}H_{16}$	bp 155° C	fp −55° C	sp gr 0·858
Aniline	$C_6H_5NH_2$	bp 184° C	fp −8° C	sp gr 1·03

Table III prepared by R. W. Stutchbury, Aircraft Propulsion Department, College of Aeronautics, Cranfield.

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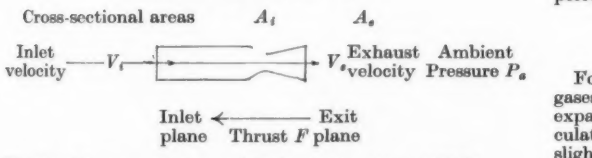
APPENDIX

Derivation of Specific Impulse



The total force exerted on a duct in the direction of flight

$$= F + P_a(A_e - A_i) = \text{change of stream thrust}$$

$$= (\dot{m}_e V_e + p_e A_e) - (\dot{m}_i V_i + p_i A_i).$$

In rocket engines, V_i, A_i, and $\dot{m}_i$ are all zero, hence

$$F = \dot{m}_e V_e + (p_e - p_a)A_e$$

In the optimum case the nozzle will be designed to give an exit pressure equal to ambient, and the thrust expression reduces to:

$$F = \dot{m}_e V_e$$

Thrust is a measure of the size and performance of the rocket engine, but a comparison of the performance of propellants is available in the thrust produced by unit consumption rate of propellant mass. This parameter is termed "specific impulse" and is represented by the symbol I_{sp}.

Hence, $I_{sp} = F/\dot{m}_e = V_e$, in consistent units.

Since it is more convenient to deal with thrust in units of pounds force and with propellant mass in units of pounds, this expression may be written in terms of the British mixed (Engineers') unit system, as follows:

$$I_{sp} = \frac{F(\text{lb})}{\dot{m}_e(\text{lb/sec})}, \text{ by definition}$$

$$\text{Therefore, } I_{sp} = \frac{F(\text{pdl})}{32{\cdot}174\dot{m}_e(\text{lb/sec})}, \text{ in consistent British absolute units}$$

$$\text{and also, } I_{sp} = \frac{F(\text{lb})}{32{\cdot}174\dot{m}_e(\text{slug/sec})}, \text{ in consistent Perry units}$$

$$= \frac{V_e}{32{\cdot}174}$$

where 32·174 is the conversion factor between the various systems of units.

V_e can be determined by applying the Bernouilli expression to the inlet and exit planes of the propelling nozzle:

$$\tfrac{1}{2}V_c^2 + C_pT_c = \tfrac{1}{2}V_e^2 + C_pT_e, \text{ for isentropic conditions}$$

where subscripts c and e represent combustion chamber (nozzle inlet) and nozzle exit planes respectively. Since V_c is nominally equal to zero, this expression may be rearranged to:

$$V_e = \sqrt{2C_pT_c - 2C_pT_e}$$

In an ideal gas, C_p is constant, hence:

$$V_e = \sqrt{2C_pT_c(1 - T_e/T_c)}$$

This may be developed from thermodynamics as follows:

$$V_e = \sqrt{\frac{2\gamma}{\gamma - 1}RT_c\left[1 - (p_e/p_c)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$= \sqrt{\frac{2\gamma}{\gamma - 1}\frac{GT_c}{M}\left[1 - (p_e/p_c)^{\frac{\gamma-1}{\gamma}}\right]}$$

where M is the mean molecular weight of the product gases.

This expression is sometimes written as $V_e = \theta\sqrt{GT_c/M}$, since the term comprising θ appears in a number of other performance parameters. Hence,

$$I_{sp} = \frac{\theta}{32{\cdot}174}\sqrt{\frac{GT_c}{M}}$$

For simplicity, the chemical composition of the combustion gases may be assumed to remain constant throughout the expansion in the propelling nozzle. Specific impulse calculated under these "frozen equilibrium" conditions is slightly less (approximately 8 per cent) than that obtained in the "shifting equilibrium" case, which includes the heat released by recombination of the free atoms and radicals due to the falling temperature.

For operation within a gaseous atmosphere, where aerodynamic drag is significant, specific impulse may be based upon propellant liquid volume, in the same way as heating value. This is expressed as the product of I_{sp} and density, and is termed the volume impulse (or density impulse).

In the ramjet engine, designed for operation within the earth's atmosphere, fuel effectiveness may be expressed in terms of the air specific impulse, which is the thrust produced with unit mass consumption rate of air. This parameter also indicates the size of engine necessary for a given thrust level.

ROLLING BEARING PERFORMANCE TEST FOR LUBRICATING GREASES *

By THE MECHANICAL TESTS PANEL OF IP STANDARDIZATION SUB-COMMITTEE D

INTRODUCTION

It is generally agreed that there is no adequate substitute for mechanical performance tests of lubricating greases to evaluate their ability to lubricate rolling bearings in industrial machinery. Such tests usually consist of running a rolling bearing with an initial charge of grease for a specified period under controlled conditions; the performance of the grease is evaluated by assessing the conditions of both the bearing and grease at the end of the run. At present many different rigs using various bearings and test conditions are in operation, and it is evident that similar results cannot be expected from these rigs under their normal operating conditions, because of the different demands each rig imposes on the grease. A need was shown therefore to develop a rig having a wider acceptance for the assessment of the performance of greases in rolling bearings for adoption by the IP.

This paper describes the development of the proposed rig, from its inception to the final form described in IP 168/59 Tentative.

The rig was developed to embody many of the features of existing rig tests.

DEVELOPMENT OF THE RIG

At the outset of this work it was agreed that the rig should be simple to operate and that the results should be capable of interpretation by those without specialized knowledge of greases and rolling bearings.

After considerable discussion it was decided to adopt a design with two bearing assemblies mounted on a horizontal spindle capable of being run at speeds up to 10,000 rev/min. Provision was made for heating the test bearings up to 150° C and to load them up to 300 lb radially. The basic design of the rig is illustrated in Figs 1–3.

The test bearing selected was a BRM-040 single row ball bearing, which is a type most commonly used in industry. This bearing differs for each manufacturer in detail with respect to cage material, pocket design, and cage float. Initially, bearings were used at random, but later it became apparent that bearing differences were affecting test precision. It was therefore decided to specify a bearing with a riveted pressed steel cage and to impose tolerances on the initial radial float on the cage.

From the beginning, the design of the test housing and its internal dimensions for the grease cavities were closely specified, as shown in Fig 4. The location and dimensions of the oven and the position of the electrical heaters were specified.

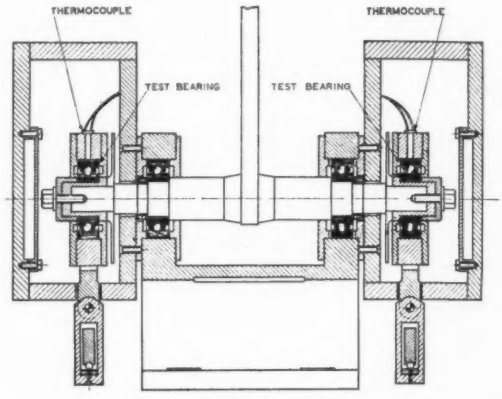


FIG 1

IP ROLLING BEARING GREASE TESTER SECTION ON CENTRE LINE

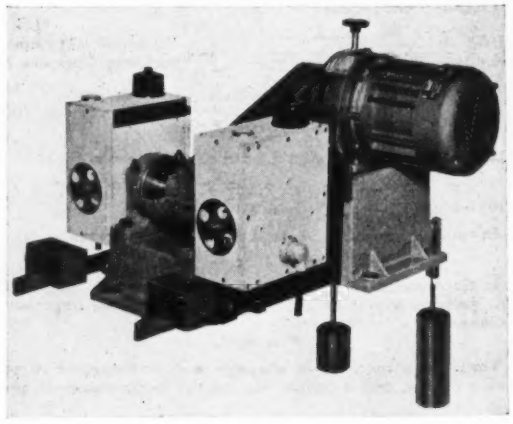


FIG 2

IP ROLLING BEARING GREASE TEST RIG

So far as the support bearing assembly and method of loading of the test bearings were concerned, the design and the rigidity of these features were not

* MS received 2 June 1960.

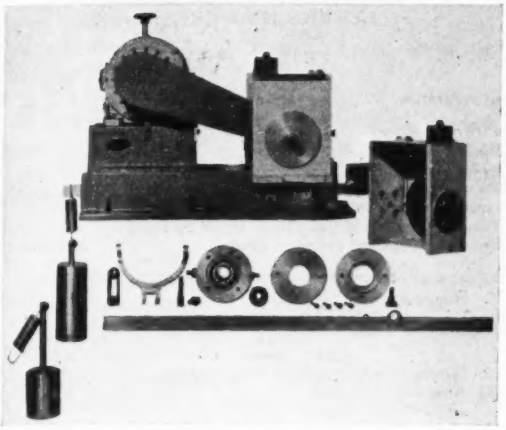


FIG 3

EXPLODED VIEW OF JP ROLLING BEARING GREASE TEST RIG

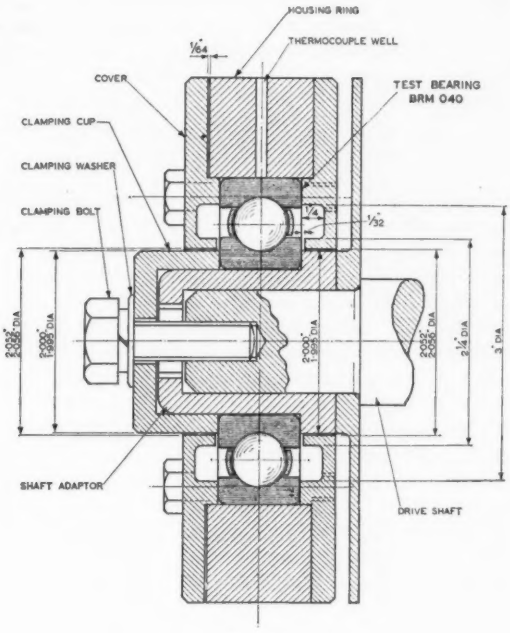


FIG 4

ESSENTIAL DETAILS OF TEST BEARING ASSEMBLY

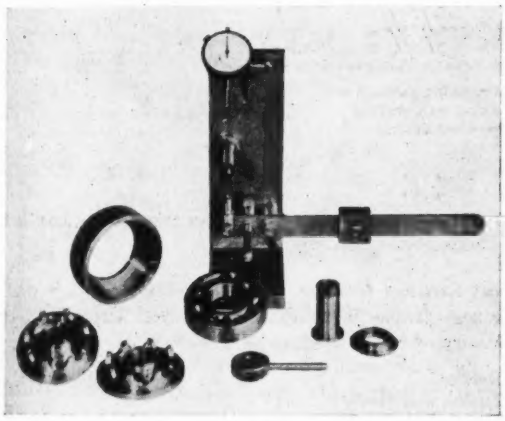


FIG 6

EXPLODED VIEW OF CAGE FLOAT MEASURING FIXTURE, SHOWING THE DIFFERENT PARTS

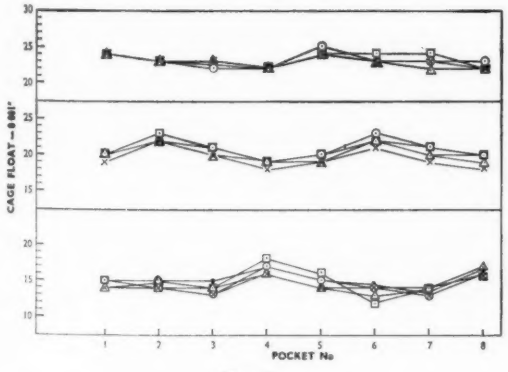


FIG 7

TYPICAL CAGE FLOAT MEASUREMENTS

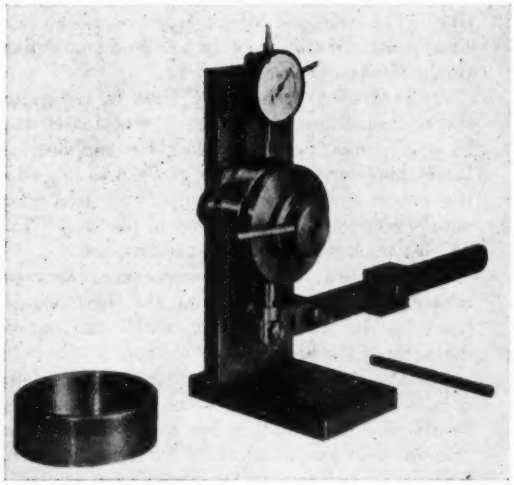


FIG 5

CAGE FLOAT MEASURING FIXTURE ASSEMBLED READY FOR USE

originally specified. Finally, however, it was found necessary to specify these features in essential detail to ensure steady and accurately running test bearings.

DEVELOPMENT OF CAGE FLOAT MEASUREMENT FIXTURE

One of the major test criteria was the assessment of the grease's ability to prevent wear occurring at the contacts where the balls rub on the cage pockets. A quantitative measurement of cage wear which could be determined from a change in cage float was therefore sought. Various methods of measuring cage float were examined by the co-operative laboratories, and the design illustrated in Figs 5 and 6 was found to be the most satisfactory, repeatable measurements being easily obtained without special skill on the part of the operator. A graph (Fig 7) representing several obtained in a correlation programme demonstrates the reproducibility of this apparatus when using three different bearings at four different laboratories. The method of using the cage float measuring fixture is fully described in IP 168/59T, Section 6 (*e*).

DEVELOPMENT OF THE TEST METHOD

For the various series of tests carried out, particular attention was paid to the following aspects of test procedure:

(1) A new bearing was used for each test and just prior to assembly the bearing was washed by lightly spinning it in successive quantities of cleaning solvent until clean from rust preventative. The removal of rust preventative was considered essential in order to avoid contamination of the test grease.

(2) Following preliminary tests to determine the optimum grease charge, it was found that 28 ± 1 g was the best filling for the bearing. With this bearing charge no grease was placed in the cover cavities, thus simplifying and more closely controlling the method of packing. This bearing pack was therefore standardized.

(3) The test bearing temperature was accurately measured by locating the thermocouple bead in intimate contact with the outside diameter of the bearing near the top.

(4) The co-operating laboratories reported full details of their operating conditions and of their results for examination by the Panel. (From this information a standard form for reporting was developed and finally the design shown in Fig 8 was adopted.)

Qualitative assessments on the condition of the grease and apparent bearing wear were not closely

ROLLING BEARING PERFORMANCE TEST
LUBRICATING GREASE

TEST REPORT

Test reference..... Grease description or ref.....

Conditions of test
Speed, rev/min..... Radial load .....
Temperature condition .....
Duration.....
Grease charge to bearing 28 ± 1 g (none in covers)
Bearing BS–BRM 040 (40 × 90 × 23 mm)
Specially selected for cage float

Summary of observed temperature operating conditions
(1) Bearing peak, ° C .....
(2) Bearing settled, ° C min .....
max .....
mean .....
(3) Hours to reach settled temperature .....
(4) Ambient, ° C, min .....
max .....
mean .....
(5) Difference between (2) and (4), mean.....(for unheated tests only)

	Rating
Leakage rating	.....
Used grease rating	
(i) Softening or hardening	.....
(ii) Other changes (remarks only)	.....
Lubrication rating	.....
Bearing wear rating	.....
Cage wear rating	.....

FIG 8

defined, but experience gained on these tests had led to the following ratings:

(*a*) *Leakage Rating.* The assembly, together with the test grease, is weighed before and after the test and any leakage rated as follows:

Rating	1	2	3	4
Loss in weight of assembly, g.	less than 1	1–5	>5–10	Above 10

(*b*) *Used Grease Rating.* The used grease is compared with the unused grease and the extent to which the used grease has changed determined.

(i) Softening or Hardening. This is estimated by touch, and rated as follows:

Rating	1	2	3	4
Softening or hardening	Unchanged	Slight	Uneven	Much

(ii) Other marked changes, *e.g.* colour and/or texture are reported.

(*c*) *Lubrication Rating.* The bearing is examined and rated for lubrication quality as follows:

Rating

(1) Bearing surfaces greasy or oily with even distribution of unchanged grease in the covers.

(2) Bearing surfaces greasy or oily, grease in covers showing marked physical change.

(3) Bearing discoloured and showing lacquer or hardened grease.

(4) Bearing dry and/or traces of metal particles discernible in the grease.

(*d*) *Bearing Wear Rating.* After washing the bearing in cleaning solvent until clean and free from grease, etc., the bearing is examined and rated as follows:

Rating

(1) Smooth, no apparent wear in comparison with a new bearing. Determined by feel and also by listening while the inner race is held in the fingers and the outer race is spun.

(2) Slight roughness. Determined by feel and by listening while the inner race is held in the fingers and the outer race is spun.

(3) Bearing very rough and with readily apparent increase in slackness between inner and outer races.

(*e*) *Cage Wear Rating.* By measuring and recording the cage float for the eight numbered positions of the cage before and after test, the cage wear was calculated and rated as follows:

Rating	Mean cage float increase, inch
(1)	0–0·005
(2)	0·006–0·010
(3)	0·011–0·015
(4)	greater than 0·015

Operating Conditions for the Co-operative Work

A maximum continuous spindle speed of 7000 rev/min was used on the co-operative work, since members of the Sub-Panel who had experience with the type of bearing concerned considered this speed to be at the upper limit when grease lubrication was used. The exploratory work of the co-operating laboratories was carried out on a variety of greases to determine the degree of temperature control obtainable and to establish peak and settled running temperatures. Tests were completed under " no applied heat " conditions and also with heat applied to control the bearing temperature at 60° C, this latter temperature being representative of the bearing temperature obtained in large electric motors.

The bearings were subjected to a radial load of 300 lb, which is the maximum that can be applied without causing excessive deflexion of the test spindle.

A test period of 500 hours was adopted, since this was considered the shortest time that could reliably be used for forecasting the lubricating ability of the grease. On commencing the test the bearing had to run continuously for at least 50 hours to obtain full data on peak temperatures and time to reach a settled temperature. Following this, the test was stopped at week-ends and allowed to cool to room temperature before re-starting.

Three groups of six greases were used for the co-operative programme, these groups covering, respectively, greases of good, borderline, or poor performance, in high-speed rolling bearings in service:

Group 1. Three sodium and three lithium base greases of known satisfactory performance in service (greases A, B, L, P, Q, S).

Group 2. Three conventional calcium base greases and three general service calcium base greases which had passed the Timken Heat Stability Test. These greases were considered unsuitable in service for high-speed rolling bearings (Greases C, D, G, H, N, O).

Group 3. Six sodium base greases which were known to give doubtful lubrication in service at high speed (Greases AA, AB, AC, AD, AE, AF).

WORK CARRIED OUT AND RESULTS OBTAINED

Eight series of tests were carried out, and the results are summarized in Table I. For the purpose of examining the performance of the greases in the IP rig, the table has been rationalized into three sections. Some of the series were duplicated due to the examinations made on the effects of different manufacturer's bearings in the various rigs and of the effects of cage material.

TABLE I

Details of Greases Examined and their Performance Level Assessed in the IP Bearing Rig Test

Test Series No.	Grease ref.	Soap type	Expected performance based on field experience under high-speed conditions	IP Performance Test Rating			
				At natural temperature		Artificially heated at 60° C	
				Number of passes	Number of failures	Number of passes	Number of failures
1, 2, and 5	A	Li	Pass	6	1	7	2
	B	Na	Pass	5	1	8	1
	L	Li	Pass	5	2	6	3
	P	Li	Pass	7	0	8	1
	Q	Na	Pass	6	1	5	3
	S	Na	Pass	4	2	6	3
3 and 4	C	Ca (T)	Poor	0	11	—	—
	D	Ca	Poor	1	10	—	—
	G	Ca (T)	Poor	1	11	—	—
	H	Ca	Poor	1	12	—	—
	N	Ca	Poor	3	11	—	—
	O	Ca (T)	Poor	3	9	—	—
(T represents greases which passed Timken Heat Stability Tests)							
6, 7, 8	AA	Na	Borderline	0	9	1	2
	AB	Na	Borderline	2	7	1	2
	AC	Na	Borderline	3	7	1	3
	AD	Na	Borderline	3	7	1	3
	AE *	Na	Borderline	8	1	2	2
	AF *	Na	Borderline	8	1	3	1

* These two greases were later stated to be suitable ball bearing greases except at high temperatures and would therefore be expected to pass the natural temperature test.

The three sections were as follows:

SECTION I

Series 1. No applied heating and employing Group 1 greases.

Series 2 and 5. Applied heating at 60° C and employing Group 1 greases.

SECTION II

Series 3 and 4. No applied heating and employing Group 2 greases.

SECTION III

Series 6 and 8. No applied heating and employing Group 3 greases.

Series 7. Applied heating at 60° C and employing Group 3 greases.

The results given in Table I include all the work done in developing the mechanical details of the rig, the choice of the test bearing covering brass *v.* steel cages and limitations on cage float. The criteria of failure are described in paragraph 1 of the discussion.

DISCUSSION

For the purpose of comparing test results, arbitrary criteria for pass and fail have been chosen. These do not, however, presume a recommendation for grease performance in general and are related only to performance under the particular IP rig test conditions discussed. A result which indicated at the most only minor changes in the condition of bearing and grease was given a pass, whereas major changes (*e.g.* cage wear, rough running, grease escape, or liquefaction) were accordingly assessed failures.

With Group 1 greases, where pass results were forecast from field experience, 33 of the 40 tests gave pass results on the tests without applied heat, and 40 of the 53 tests gave pass results with applied heating, despite the variation in the test techniques and equipment that existed. It was not clear, until the correlation programme was nearly complete, which of the various co-operating laboratories' techniques and equipments (*i.e.* uniformity of applying load and rigidity of test bearing) should be adopted as standard.

In the case of Group 2 greases, where fail results were forecast, 64 of the 73 tests failed. These greases were not examined with applied heating at 60° C in view of the high incidence of failures. In the majority of cases failures were due to the grease liquefying and giving excessive leakage.

With Group 3 greases, which were forecast as being borderline, 24 of the 56 tests gave pass results on the tests without applied heat and nine of the 22 tests gave pass results with applied heating. It will, however, be seen that two greases (AE and AF) in this series each gave eight passes in nine tests, which did not agree with the reported borderline performance. It transpired later that these two greases were suitable ball bearing greases except at high temperature, and thus should have passed the test conditions without applied heating. It would therefore be a fairer assessment of the borderline greases if these two greases were not considered; then only eight of the 38 tests gave pass results.

The influence of cage metals and cage float on performance, and the results obtained using greases which were satisfactory in service, are illustrated in Table II.

TABLE II

Grease group	Tests with or without applied heat	Number of tests results/number of failures		
		Steel cages		Brass cages
		Cage float range 0·015–0·030 inch (IP Standard)	Cage float range >0·030 inch	Cage float range 0·015–0·030 inch
1	Without	18/1	10/6	12/0
	With	18/3	18/6	17/2

From these results there was every justification for specifying that the test bearings should have cage floats in the range 0·015–0·030 inch, since above this range the incidence of cage wear was greater. Although with the brass cage bearing performance was good, it was not intended that this type would be considered for the IP rig because the bearing manufacturer concerned was about to change to steel cages for the size and type of bearing used in the IP rig.

Since the cage float influences performance, it is of interest to examine the results in terms of tests carried

TABLE III

Variation in Peak/Settled Temperatures/Hours to Settle

Grease	Peak temperature range, ° C	Settled temperature, ° C (above ambient) range	Hours to settled temperature range
A	43–78	5–26	2–48
B	73–98	8–23	9–48
L	35–95	4–20	4–24
P	40–90	6–21	6–53
Q	46–84	3–15	5–24
S	35–81	7–19	3–24
C	60–96	17–28	15–42
D	70–100	2–36	2–60
G	95–111	*	*
H	54–118	*	*
N	75–118	9–30	1–48
O	58–124	7–21	1–48
AA	43–88	7–31	1–22
AB	43–114	7–78	1–14
AC	41–95	6–15	1–4
AD	39–76	7–26	1–24
AE	41–116	4–19	2–24
AF	45–89	6–20	1–24

* Settled temperatures not reached.

out with bearings which met the standard that would be adopted by the IP (*i.e.* bearings with cage floats in the range 0·015–0·030 inch). It will be seen from Table II that only one test in 18 failed on tests without applied heat and three tests in 18 failed on tests heated at 60° C, using greases of known satisfactory field performance.

Work carried out between co-operating laboratories on the interchange of bearings did not produce anything conclusive, except that bearings which had cage floats within the limits specified by the IP gave better repeatability and reproducibility.

The variations in peak temperature, settled temperature, and time to reach a settled temperature were checked, and the results are summarized in Table III. They show considerable variation, but the range is within the limits normally experienced in other high-speed rolling bearing grease tests.

CONCLUSIONS

1. The rigs which were used in the co-operative work gave results which correlated well with the known field performance of the various greases examined, despite certain differences in rig design outside the test bearing assembly.

2. The results of tests which used bearings with cage floats restricted to 0·015–0·030 inch gave better repeatability and reproducibility than those with cage floats in excess of this figure.

3. The successful development of a cage float measuring fixture made possible the determination of smaller differences in grease performance.

4. There were considerable differences in peak temperatures, settled temperatures, and times to reach a settled temperature. The variation was, however, within the range obtained in other high-speed rolling bearing grease tests.

5. Work was not specifically carried out to determine the effect of rigidity of support for the test spindle and the method of radial loading of the test bearings. However, it was considered necessary that the rig should be standardized in every essential feature, and the rig illustrated in Figs 2 and 3 was finally chosen.

6. The oven design, heater position relative to the test bearing, and location of the thermocouple as initially conceived were adequate, and no development of these features was necessary. The oven temperature could be controlled within $\pm 2°$ C at the test temperature of 60° C.

7. The results obtained from the co-operative programmes qualified the introduction of the Rolling Bearing Performance Test for Lubricating Greases as an IP Tentative Standard Method (IP 168/59T).

FURTHER WORK

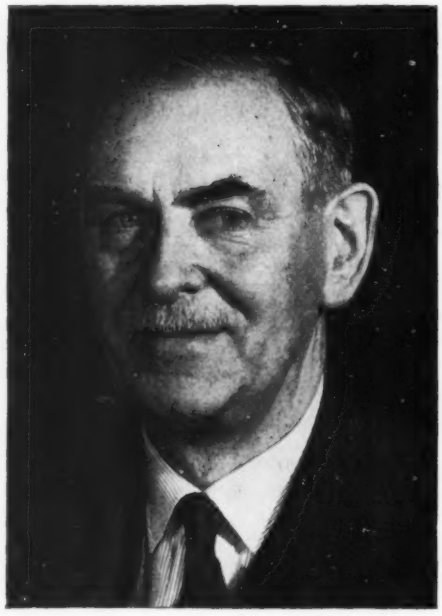
A further correlation programme is being conducted employing the standardized IP rigs in order to assess the repeatability and reproducibility of the method when using a variety of greases at various operating speeds and temperatures. Steps will be taken to try to reduce the difference in peak and settled temperatures.

OBITUARIES

GEORGE WILLIAM DUNKLEY, O.B.E.

1892–1960

THE death of George Dunkley on 30 July after a serious, but mercifully brief, illness came as a great shock to his many friends in the industry. A few months ago we all thought that he was in the heyday of happy retirement. Only last April, when asked whether he had put his boat into the water, he replied with characteristic serenity: " There is no hurry, the weather is a bit dicey and there is all the summer for yachting." How tragic those words sound now that he will no more relish the tang of salt on his lips and the exhilaration of flying spume.



He was educated at St Albans School and Pembroke College, Cambridge, where he read mathematics and became a Wrangler. Entering the London Office of the Anglo-Persian Oil Company in 1914, he acted as secretary to the late Lord Greenway before serving in the Royal Marine Artillery in the first world war. His mathematical ability was put to good use on ballistics work at the Admiralty, for which he was awarded the O.B.E. He rejoined the Anglo-Persian Oil Company in 1919, and after four years with their agents in India served for eight years in Persia, before being seconded to the Iraq Petroleum Company.

George Dunkley was essentially a modest man, and few but his immediate associates realized the major part he played, with the late J. Skliros, the late M. M. Stuckey, the late H. H. Wheatley, Sir Stephen Gibson, and G. H. Herridge (the present managing director) in building up the Iraq Petroleum Company. He was lent by the Anglo-Persian Company in March 1931 to take charge of the company's affairs as agent in Palestine, Transjordan, Syria, and the Lebanon. In March 1935 he was appointed General Manager in the Middle East. In these capacities he was at the centre of affairs during the construction of the first trans-desert pipelines, culminating in the export of oil from Iraq in July 1934, and the build-up of Iraq production to 4 million tons, the pre-war capacity of the pipeline system.

Early in the second world war his services were placed at the disposal of the War Office as a member of the Standing Committee on Army Administration under the chairmanship of Sir James Grigg. In January 1942 he was attached to the Minister of State in Cairo as Petroleum Adviser in the Middle East, returning to the Iraq Petroleum Company in January 1944. As a member of management in London and, from 1951, as an executive director, he had a special responsibility for planning and construction, including the 16-inch pipelines from Kirkuk to the Mediterranean and of the 30-inch pipeline to Banias, which raised Kirkuk production to 6 million tons in 1950 and to 24 million tons by 1955. At the London headquarters of the Iraq Petroleum Group of Companies he worked in complete harmony with three successive managing directors as a loyal and valued colleague, unobtrusive in tranquil times and steadfast in time of stress. In all his dealings with subordinates—a term he would never have used, for to him we were all colleagues—he was the soul of honour: slow to interfere, but always ready with counsel and support when approached.

At Cambridge he rowed in the Pembroke second May Boat, and when in India rowed for the Karachi Boat Club. He retained a keen interest in sport, May Week and the 'Varsity soccer match being the red-letter days in his sporting calendar. His two main recreations, however, were yachting and music. To the latter he brought an appreciation which stemmed from his early training and sustained interest in mathematics and which surpassed that of many performing devotees.

In forty-five years association with the oil industry —he retired in 1958—George Dunkley received many honours, including Chevalier of the Legion of Honour, the Order of Al Rafidain (Iraq), the Order of Istiklal (Jordan), and the Order of Merit of the Lebanese Republic. Of much greater importance to him was the affection and esteem of his colleagues, who cherish the memory of his humanity and his generosity, both of means and mind.

He leaves a widow and two daughters, whose loss we share and to whom our sympathy goes out.

C. T. B.

EDWARD JASPER HORLEY
1894–1960

E. J. HORLEY, who died at his home in Broadstairs on 29 May 1960, joined the British Petroleum Company in February 1913.

After service during the first world war, when he campaigned in France and Belgium, attaining the rank of Major, Mr Horley returned to the Company in November 1919 and was posted to the Anglo-Persian Oil Company's Research Department at Sunbury and served there until October 1921.

From November 1921 until his retirement in July 1954, Mr Horley was stationed at Llandarcy, starting his career in the refinery as a shift superintendent. During the second world war he served as head of the ARP Organization and as officer commanding the Llandarcy Company of the Home Guard; at the time of his retirement Mr Horley was the technical information officer.

Throughout his association with the industry Mr Horley was an active and energetic member of the Institute of Petroleum, which he first joined in 1920. He was a founder member of the South Wales Branch of the Institute and served as its honorary secretary until his retirement; he had been an ex-officio member of the Council as well as a member of the Publications Committee.

P. F. E.

WILLIAM HARDWICK NIEL
1909–1960

THE death occurred on 17 June of William Hardwick Niel, chief accountant at Esso Refinery, Fawley, at his home, Seaclose, Ashlett Lane, Fawley.

Mr Niel, who was aged 50, was appointed chief refinery accountant in 1957. He had been seriously ill for some time before he died. Born in Newcastle, Bill Niel joined the staff of the Cost Office of the AGWI Refinery at Fawley in 1927. During the rapid expansion of the refinery since 1949, he played a considerable part in developing refinery accounting procedures to meet the increased work.

Bill Niel was much liked and respected by other members of the refinery staff. He combined a tremendous enthusiasm for his work with sound Northern common sense and considerable human sympathy. Away from the office he was a great lover of his home and a keen motorist. He leaves a widow, to whom we offer our sincere condolences.

S. A. B.

ROBERT ILLTYD LEWIS

ALTHOUGH he had not been in good health for some time, the sudden death of R. I. Lewis on 17 August will come as a blow to his very many friends in the petroleum industry.

Educated in Merthyr Tydfil County School and the University College of South Wales and Monmouthshire, Cardiff, Mr Lewis obtained his honours degree in chemistry in 1913—one of the earliest men, possibly the earliest, to obtain a honours degree in three years' residence at the University.

On graduation he entered industry, and during the first world war was employed on munitions. At the end of the war he joined the oil industry in the Burmah Oil Company and spent some years in Burma. He entered the Shell Company in 1925 and after a short time at Shellhaven went to California, where he was in charge of the laboratory at the Wilmington refinery. Later he moved to San Francisco and, on the establishment of Shell Eastern, was appointed chief chemist, first at Boston and later with headquarters in New York. He returned to Britain on the outbreak of the second world war and remained in charge of the chemical department of the Shell Petroleum Company until his retirement on account of ill-health at the beginning of 1948.

He joined the Institute in 1931 and was a Fellow until his retirement in 1948. During that period he served as a member of the Council and of the Branches and Research Committees, for a time being chairman of the latter. He was also instrumental in the foundation of the *IP Review* in that he was one of those who, in 1946, suggested an enlargement of the Institute Notes then appearing in the *Journal*. As a result, the *IP Review* came into being in January 1947.

" Bob," as he was known to all his friends in the industry, was a good chemist and had a keen analytical brain. He was always a very cheerful companion, both in the office and outside. I can never remember him ruffled or bad-tempered, nor do I think that any of his friends can remember such occasions. He will be sadly missed by his many friends, and our sympathies go to his very devoted wife, who, as we all know, had as many friends in the oil industry as did Bob himself.

J. A. O.